AN EXPERIMENTAL COURSE
IN THE
FUNDAMENTAL PRINCIPLES
OF RADIO

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FOREWORD

It is a very pleasant task to write an introduction to this series of laboratory experiments devised by a member of my staff.

The extent to which Technical Colleges have been requested to aid the national effort during the past four years by arranging courses for those who are to enter essential industries and those undertaking skilled occupations in the Forces is very gratifying to all concerned with technical education.

The objective of some of these courses is the acquisition of skill in the use of certain tools, but the purpose of other courses is the inculcation of a knowledge of the principles underlying a specific trade or industry.

It is in this latter connexion that this book has been produced and it should contribute to the store of knowledge of those who have to construct, operate, and service radio apparatus.

GEO. PATCHIN

THE SIR JOHN CASS TECHNICAL INSTITUTE
LONDON

August, 1944

PREFACE

THIS practical course is based on one which has been developed as part of a course of training given to those who have little or no knowledge of electricity and magnetism. It is intended to be used in conjunction with courses of lectures covering the same ground. Throughout the work, attention has been paid to the fundamental principles of the subject and I have attempted to give, in concise form, a statement of the theory underlying each experiment or group of experiments. It cannot be emphasized too often that the rule of knowledge should always take precedence over rule of thumb methods in radio work.

Many of the experiments in this course are of an elementary nature, and should be well within the scope of any physics laboratory which has simple radio equipment. The order in which the experiments are made should be related to the order followed by the associated lecture course. It may also be dependent on the apparatus which is available. I have, therefore, set out the course in chapters, the order of which follows that in which the subject is best treated, and, in each chapter, the experiments have been arranged as far as possible in what seems to be a suitable order from the educational point of view. It is not suggested, however, that all the experiments in the later chapters, particularly those on valve characteristics, should be performed consecutively.

The difficulty of choosing valves from the very large number which appear in makers' catalogues has been resolved, at the risk of criticism for not using the latest types, by selecting the simplest type for any experiment, bearing in mind that the fundamental principles can be illustrated without resorting to a large and confusing variety of valves.

Limitations of space have made it impossible to include representative results of each experiment in a tabulated form and some mention should therefore be made of the importance of setting out all readings and results in a proper manner.

In normal times a course of this nature might well extend over eighteen months, the first half of which would cover the electrical circuit theory and the simple treatment of valves, while the second half would deal with the radio circuit theory.

I am indebted to Mr. Geo. Patchin, A.R.S.M., who kindly consented to write the Foreword, for the suggestion that the course should be published and for his interest in the work. My best thanks are tendered to him and also to Dr. D. Owen, under whose direction a course of this kind was initiated. I would also express my appreciation of the assistance given by my colleagues, Mr. G. F. Aylard, Mr. L. G. Dive, Mr. S. H. Filby, B.Sc., Mr. T. Hutchinson, B.Sc., Mr. H. L. Jolley, B.Sc., and Mr. J. Yarwood, B.Sc., in many helpful discussions. Mr. C. W. Celia, M.Sc., has, from time to time, made suggestions, which have been incorporated here, for the improvement of the experiments and I am very grateful for his help in this and in other ways.

R. H. HUMPHRY

LONDON

August, 1944

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GENERAL RULES
FOR THE ELECTRICAL LABORATORY

In connecting electrical circuits and making measurements, the following rules will be found useful and they are intended to be applied throughout this experimental course—

Before connecting any circuit, draw the circuit diagram on paper.

Include a main switch in every circuit and see that it is open before making any connexions.

A fuse of suitable value will protect instruments, valves, and other apparatus from damage by overloading. This applies particularly to circuits using the supply mains.

Always check the connected circuit before switching on. Look for loose contacts and make sure that D.C. instruments are connected with correct polarity.

See that the instruments to be used are of suitable range for the particular measurement. When instruments have several ranges, always commence with the highest range.

In general, set controls so as to commence with the lowest values of current, voltage, etc.

Remember that a measurement with any instrument involves two readings—the zero reading, which may not be 0, and the reading when deflected.

Express all measurements in their proper units and record readings and results, as far as possible, in a tabular form.

At the conclusion of the observations, switch off and disconnect first at the supply terminals.

COLOUR CODE FOR RESISTORS

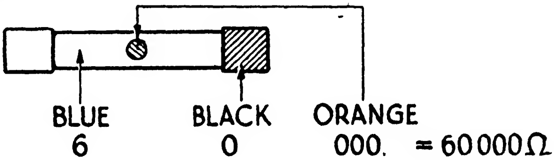
THE value in ohms of resistances used in radio circuits is often indicated by the colour code shown below.

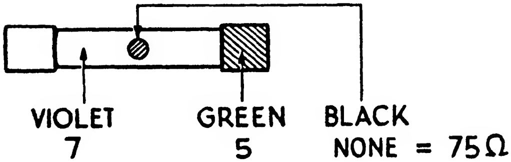
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

The colour of the body of the resistor gives the first figure, the colour of the tip gives the second figure, and the colour of the spot gives the number of 0's following these two figures.

If there is no spot visible, it is of the same colour as the body.

Examples:





An article on colour coding as applied to resistors, condensers, and transformers has been published recently by Parr in the *Jour. Sci. Instr.*, Vol. 20, p. 121, 1943.

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CHAPTER I

SIMPLE D.C. EXPERIMENTS

THE three principal sources of supply in a laboratory are the primary cell, the secondary cell or accumulator, and the mains, the last-named providing either direct current (D.C.) or alternating current (A.C.). A working knowledge of these sources is essential at the outset of a practical course.

Experiment 1. Cells and their Electromotive Forces

The Leclanché cell is a primary cell, which has two forms, a wet form and a so-called dry form. The construction of each type may be examined by cutting through old porous pots of the wet cell or old dry cells with a hacksaw. The wet cell has a zinc negative pole and a carbon positive pole immersed in a solution of sal-ammoniac. The positive pole, contained in a porous pot, is surrounded by the depolarizer, which is a mixture of manganese dioxide and carbon powder. The dry cell is constructed of the same materials, except that a paste of sal-ammoniac with zinc chloride is used in place of the solution. The negative pole is the zinc case. Dry cells are more convenient to use and, when new, have a much lower internal resistance. Primary cells are not used to supply large currents, but they are useful (as in high-tension or flash-lamp batteries) when small currents are required, or they are used for very short periods of time.

The lead-acid accumulator is a secondary cell, which, in the charged condition, has positive plates of lead peroxide, chocolate-brown in colour, and slate-grey negative plates of

lead. The terminals are red (+) and black or blue (—). The plates stand in dilute sulphuric acid whose specific gravity is from 1·270 to 1·170, depending on the state of the cell, the value being highest when the cell is fully charged.

The *electromotive force* (E.M.F.), E, of a cell is expressed in volts and is measured practically by connecting a voltmeter to the terminals, the positive pole of the cell being joined to the + (or red) terminal of the voltmeter. The E.M.F. of a wet or dry Leclanché cell is about 1·5 volts, while that of a lead accumulator is about 2 volts.

If cells are joined in series, the total E.M.F. is the sum of

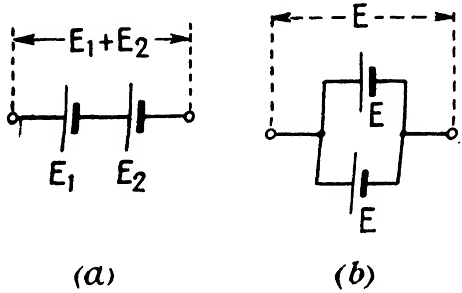

FIG. 1. CELLS: (*a*) IN SERIES; (*b*) IN PARALLEL

the individual E.M.F.s. Thus, as shown in Fig. 1 (*a*) for two cells whose E.M.F.s are E_1 and E_2, the combined or overall E.M.F. is given by $E = E_1 + E_2$.

If cells of equal E.M.F. E are joined in parallel, as shown in Fig. 1 (*b*), the overall E.M.F. is E.

These relations should be tested in the following way—

(i) Measure with a voltmeter (0–5 volt range) the E.M.F. of individual cells of the above types.

(ii) Connect some of these cells in series, say two Leclanché cells or a Leclanché cell and an accumulator, and measure their combined E.M.F., showing that, within the limits of experimental error, it is equal to $E_1 + E_2$.

(iii) Connect two dry cells in parallel, measure the E.M.F. of this arrangement and confirm the law for cells in parallel.

Experiment 2. D.C. Mains

These provide a supply at a much higher voltage than a cell, the value being usually 200, 220, or 240 volts. The

leads must, therefore, be insulated, must not be allowed to touch, and should be handled only when the switch is off. In order to measure the voltage, a voltmeter of range 0–300 volts is required, and the polarity must be known if a moving-coil instrument is used. The polarity may be tested in two ways, first by using an Osglim neon lamp, and secondly by pole-finding paper. When the neon lamp is connected to D.C. mains, the glow appears round the negative electrode. In making this experiment, note that the glow is steady (as compared with that which is obtained with A.C. mains as described in Experiment 3).

Pole-finding paper is used in the following manner. A piece of the paper is damped with water, and the leads from the mains with a lamp in series are held about 2 in. apart on it. A coloured stain appears on the paper around one of the leads. A statement on the packet of paper will indicate what is the polarity of that lead.*

Experiment 3. A.C. Mains

Although this chapter is concerned with D.C. experiments, it is wise to know something of the A.C. supply commonly used. The frequency of alternation in direction of current or voltage is usually 50 cycles per second (c/s) and a common voltage is 230 volts. This value is not, however, the greatest or peak voltage, but is the effective voltage of the supply, and is called the root-mean-square (R.M.S.) value. The peak voltage is $\sqrt{2}$ or 1·414 times the R.M.S. voltage. In the case of 230-volt mains, therefore, the peak voltage is 325.

An A.C. supply may be distinguished from a D.C. supply, provided their voltages are in the region of the values stated, by connecting an Osglim neon lamp to the mains. With A.C., a flickering glow appears on both electrodes. The flicker can be observed more readily if the lamp is moved quickly, and is due to the glow appearing on each electrode alternately when the voltage reaches the striking potential for the gas in the lamp. As the voltage falls the glow disappears at the extinction potential.

* Pole-finding paper may be made by soaking white blotting paper in a solution containing 10 gm. of potassium chloride in 100 c.c. of distilled water, to which solution has been added 1 gm. of phenolphthalein dissolved in alcohol. The paper is then allowed to dry. When used as described, a pink stain occurs at the negative pole.

Pole-finding paper may also be used. In this case the two leads should be connected through a lamp to two metal pins fixed in an insulating plate (an ordinary 5-amp. plug will do very well) and the two electrodes should be drawn rapidly across the paper, tracing out two parallel lines. On the paper will be found two lines of coloured dashes, the spaces of one line standing opposite the marks of the other. This illustrates the alternations of polarity which occur in A.C. mains.

In order to measure the voltage, instruments of suitable type and range must be used. The two commonest types are moving-iron and electrostatic instruments. Their reading gives the R.M.S. value. A moving-coil instrument cannot be used for alternating voltages without modification.

Experiment 4. Ohm's Law

This is the most important law in electricity. It states that the current passing through a conductor is proportional to the voltage between its ends, provided the physical state (i.e. temperature, structure, etc.) of the conductor remains unchanged. The law should be taken as applying to steady currents and voltages. If $V =$ the voltage and $I =$ the current, then V is proportional to I, or $V = RI$, where R is a constant. This constant is the resistance of the conductor and is thus defined as the ratio of V to I. If V is expressed in *volts* and I in *amperes*, then R is in *ohms*.

In order to confirm Ohm's Law it is necessary to measure the current through a fixed resistance, and the voltage (or potential difference) between its ends.

In measuring the voltage, care must be taken to use a voltmeter of such high resistance that its connexion across the resistance under test does not appreciably disturb the current in the circuit or the voltage across R.

A suitable resistance for this experiment is an ordinary wire rheostat of about 10 Ω. The circuit is connected as shown in Fig. 2, the cells (6 volts), switch, ammeter (0–1 amp.), resistance R, and controlling rheostat P being all in series.

The voltmeter (0 — 10 volts) is connected across the used portion of the rheostat from which R is taken. Setting P at its maximum value and R at about half-value, the current is switched on and adjusted to 0·1 amp. by altering P. The voltage V across R is recorded. Then, keeping R fixed, the

current is adjusted to 0·2, 0·3, . . . amp. in turn and, at each value of current, the voltage is read and recorded.

Ohm's Law may then be tested in two ways. First, working out the ratio V/I for each pair of readings, the value of this

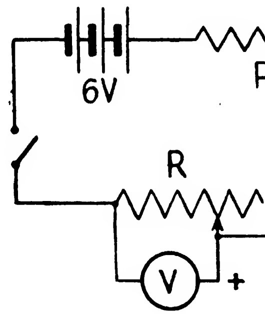

FIG. 2. TO CONFIRM OHM'S LAW

ratio should be sensibly constant, giving the resistance R. Secondly, the relation between V and I may be expressed by a graph. Choosing suitable scales, V is plotted against I as shown in Fig. 3. It will be found that the points lie on a

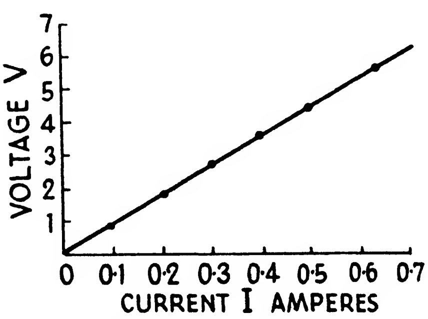

FIG. 3. LINEAR RELATION BETWEEN V AND I

straight line which passes through the origin 0. Thus V and I are connected by a linear law, which is another way of stating Ohm's Law.

A second set of readings should be taken with a different, but fixed, value of R. On plotting these readings in the same

way, a straight line passing through the origin will again be obtained, but it will have a different slope.

Experiment 5. The Resistance of an Electric Lamp

As stated above, Ohm's Law applies strictly only if the temperature of the conductor remains constant. If the temperature of the conductor depends on the current, as in an electric lamp, the relation between V and I will not be a straight line, but the resistance R is still defined as the ratio

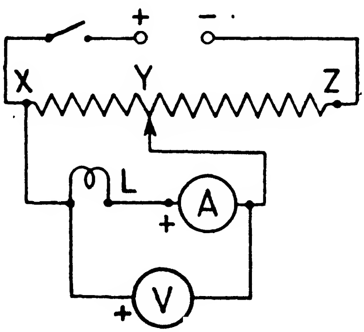

FIG. 4. CIRCUIT TO OBTAIN CHARACTERISTIC OF A LAMP

V/I. The value of R will no longer be a constant, but will depend on the voltage applied to the lamp. The purpose of this experiment is to obtain the characteristic of a lamp and to investigate how the resistance depends on the voltage. The characteristic is the curve obtained by plotting I against V.

The experiment may be carried out either with a small flash-lamp or with a lamp normally used on the mains. In the former case the supply could be 4 volts from accumulators; in the latter it will be the D.C. mains. The circuit will be as shown in Fig. 4.

The voltage to be applied to the lamp is obtained from a potential divider XYZ in order that it may be varied from 0 to the rated maximum for the particular lamp used. The supply is connected to the *ends* of the resistance XZ (which must be capable of carrying the current when it is connected to the supply without overheating) while the voltage for the lamp is tapped off from the end X and the slider Y. This voltage is applied to the lamp and ammeter (range 0–1 amp.)

with the voltmeter connected across them. If a flash-lamp is used, the voltmeter range should be 0–5 volts, but if a mains lamp is used the range of the instrument should be 0–300 volts. Similarly, the choice of rheostat XZ will depend on the voltage of the supply. If mains are used, it should be about 1000 Ω capable of carrying $\frac{1}{2}$ amp., while if cells are used, it need not be above 100 Ω.

The experiment is commenced with Y very near to X,

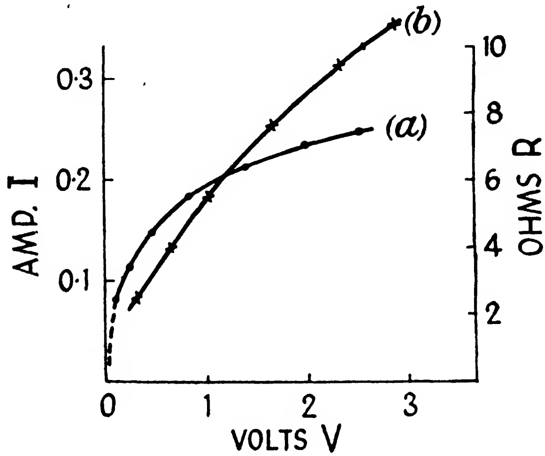

FIG. 5. (a) THE CHARACTERISTIC OF A FLASH-LAMP; (b) VARIATION OF RESISTANCE WITH VOLTAGE

(Resistance scale on the right)

thus applying a very small voltage to the lamp. A series of simultaneous readings of V and I are taken as Y is moved in steps towards Z. Care must be taken that the rated voltage of the lamp, printed upon it, is not exceeded. For each pair of values, the resistance R is calculated. Graphs are then drawn, as in Fig. 5, showing the relation between I and V and between R and V.

It will be seen that the characteristic is curved, being therefore different from the linear graph obtained with a conductor satisfying Ohm's Law.

The arrangement of voltmeter and ammeter in the above circuit should be noted. The reading for V will be a little high because the resistance of the ammeter is included, but

it gives greater accuracy than connecting the voltmeter across the lamp alone, in which case the reading for I would be a little high because the ammeter would read the current through lamp and voltmeter in parallel. The resistance of the ammeter is usually a smaller fraction of the resistance of the lamp than the resistance of the lamp is of that of the voltmeter. Thus the error is smaller in the former case. The accuracy with which R can be determined depends on the accuracy with which the instruments can be read. If desired, the

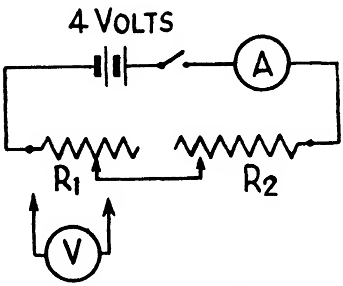

FIG. 6. RESISTANCES IN SERIES

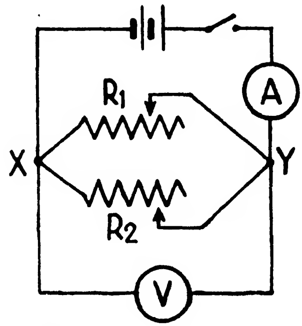

FIG. 7. RESISTANCES IN PARALLEL

resistance of the ammeter in this experiment can be readily measured by short-circuiting the lamp and using a very small voltage. It will probably be found to be negligible, but if not, can be subtracted from the calculated value of R.

Experiment 6. Resistances in Series and in Parallel

(a) When resistances R_1, R_2, . . . , etc., are connected in series, the combined resistance is given by the sum of the individual resistances, or $R = R_1 + R_2 + \ldots$.

This law may be confirmed by connecting in series two resistances similar to that used in confirming Ohm's Law (say, two 10 Ω rheostats) and measuring their separate and combined resistance by the voltmeter-ammeter method.

The circuit is shown in Fig. 6. A high resistance voltmeter is connected first across R_1, then across R_2, and finally across the two in series. If I is the current (kept constant during the measurements), while V_1, V_2, and V are the respective voltages, we have $R_1 = V_1/I$, $R_2 = V_2/I$, and $R = V/I$.

Measurements should be taken at various values of current which, to save arithmetical calculation, may be taken at 0·1, 0·2, . . . 0·8 amp. R will be found equal to $R_1 + R_2$ within experimental error.

(*b*) When resistances R_1, R_2, . . . , etc., are connected in parallel, the combined resistance R is given by the relation

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

In order to confirm this law, the components used in (*a*) are connected as in Fig. 7. The voltmeter is now connected permanently across XY. If the lead from Y to R_2 is broken, then R_1 only is in circuit and can be measured, while if the lead from Y to R_1 is broken, R_2 only can be measured. Setting the rheostat sliders so that R_1 and R_2 are at their greatest values, and bringing R_1 only into circuit, the corresponding values of the current I_1 and the voltage V_1 are read. R_2 is then brought into circuit instead of R_1, and the values of I_2 and V_2 observed. Finally, the connexion to R_1 is remade (so that R_1 and R_2 are in parallel) and the values I and V observed.

Working out

$$\frac{1}{R} = \frac{I}{V}, \frac{1}{R_1} = \frac{I_1}{V_1}, \text{ and } \frac{1}{R_2} = \frac{I_2}{V_2}$$

it will be found that, within the limits of experimental error, the law mentioned above holds good.

$\frac{1}{R}$ is termed the *conductance*. Thus, the conductance of a circuit composed of several conductors in parallel is the sum of the separate conductances.

Experiment 7. The Potential Divider and Potentiometer

(*a*) A potential divider has already been used in Experiment 5. It provides a very convenient means of obtaining any desired fraction of a given voltage. Suppose that a number of resistances R_1, R_2, . . . (ohms) are connected in series and that a current of I amps. passes through them. By Ohm's Law the p.d. in volts between the ends of R_1 is $V_1 = I \times R_1$, that between the ends of R_2 is $V_2 = I \times R_2$, and so on. If

V is the total p.d. over the resistances, then $V = V_1 + V_2 + \ldots$, and any desired voltage less than V may be obtained by tapping off from the ends of a suitable series resistance. The fraction of V which is obtained by tapping at the ends of R_1 is $\dfrac{R_1}{R_1 + R_2 + \ldots}$.

In order to test this arrangement, a rheostat of 400 to 500 Ω is connected in series with a carbon lamp (32 c.p.) and

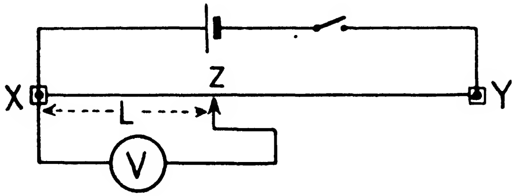

FIG. 8. SIMPLE POTENTIAL DIVIDER

a metal filament lamp (40 watts) on the D.C. 200-volt mains. Using a high-resistance voltmeter of range 0–300 volts, the potential drop across each resistance and across the three resistances is measured. It will then be apparent that $V = V_1 + V_2 + V_3$.

(*b*) For many purposes a continuously variable potential divider is required. In this case a uniform wire is used, either straight or wound on a cylinder with a sliding contact. The voltage tapped off is then proportional to the length of wire between the tapping points. For experimental work, 2 metres of No. 30 S.W.G. eureka wire may be stretched in four 50-cm. lengths between fixing plates of copper or brass on a board which is provided with a ½ metre scale and a tapping contact, so that the distance L between one end of the wire and the tapping point may be measured. This wire is shown at XY in Fig. 8, the tapping point being at Z. A 2-volt cell is connected to the ends of the wire and the voltmeter (range 0–3 volts) is connected between the end X and the slider Z. Setting L (= the distance XZ) at 20, 40, 60, . . . 180 cm. in succession, the voltage for each value is read.

In order to test whether the p.d. tapped off is proportional to L, the value of V is plotted against the value of L. If the wire is uniform, the points will be found to lie on a straight line.

The above methods of potential division are often used in radio circuits. A potential divider of the second type, using a wire or a circular strip coated with carbon, is generally called a potentiometer. Although this term has passed into common usage, it is strictly incorrect.

(*c*) The potentiometer is an arrangement which makes use of the above results in order to measure the E.M.F. of a cell or other potential differences. A simple form is shown

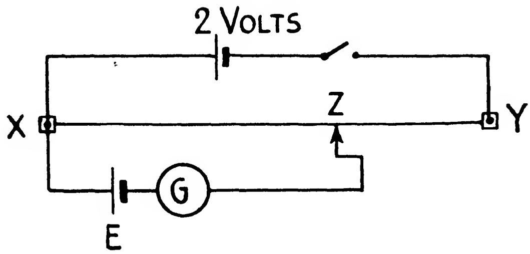

FIG. 9. SIMPLE POTENTIOMETER

in Fig. 9. XY is the uniform wire 200 cm. long, used previously, and it is supplied by a 2-volt accumulator. The cell whose E.M.F. E is to be measured (E must be less than that of the cell supplying XY) is arranged so that E is opposed to the p.d. between X and the tapping point Z on the wire. If the position of Z is adjusted until this p.d. is equal to E, then no current will flow through E. This condition is found by connecting a sensitive current measuring instrument or galvanometer G in series with E, and adjusting the position of Z until no deflexion of G occurs on making the contact at Z.

If the potential difference between X and Y is 2 volts, then

$$E = \frac{\text{length } XZ}{\text{length } XY} \times 2 \text{ volts}$$

As an example for a particular cell, suppose XZ for balance $= 144{\cdot}6$ cm., while $XY = 200$ cm.; then $E = 1{\cdot}446$ volts.

The importance of this method lies in the fact that, when balanced as described, no current passes through the cell under test and thus its E.M.F. (which is the p.d. between its terminals on open circuit) is accurately measured.

Experiment 8. Measurement of Resistance by the Wheatstone Bridge

The Wheatstone bridge is the most accurate method of measuring resistances of ordinary value, between 1 and 10,000 Ω. It consists of four resistances P, Q, R, and S, called the arms of the bridge, joined in a diamond shape as shown in Fig. 10. A cell is connected to two opposite corners, and a sensitive galvanometer G to the other two opposite corners.

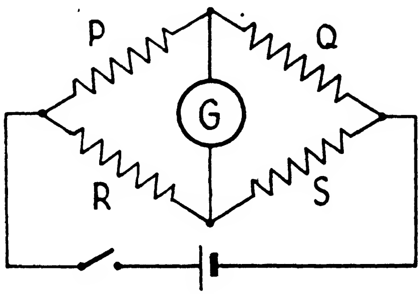

FIG. 10. WHEATSTONE BRIDGE

The bridge is said to be balanced when no current flows through G, a condition which is attained by adjustment of the resistances in one or more of the arms. When this is the case,

$$\frac{P}{Q} = \frac{R}{S}$$

If R is the resistance to be measured, then $R = \frac{P}{Q} \times S$ and may be calculated if the ratio P/Q and the value of S for balance are known.

A simple form of the bridge is the metre wire bridge shown in Fig. 11. Copper strips carrying terminals are fixed to a base board so that two gaps are provided in which the resistances R and S may be connected, while between the ends X and Y is stretched a uniform wire 100 cm. long, with a movable tapping contact Z whose position can be read on a metre-scale fixed near the wire. The resistances of the lengths XZ and ZY provide the arms P and Q, whose ratio is therefore variable.

If the length $XZ = L$ cm. (for balance), so that $ZY = 100 - L$ cm., then

$$R = \frac{L}{100 - L} \times S$$

In measuring the resistance of a coil by this method, S is a standard resistance and should be chosen so that it is approximately equal to R, i.e. the balance point is found near the centre of the wire. The accuracy of the measurement

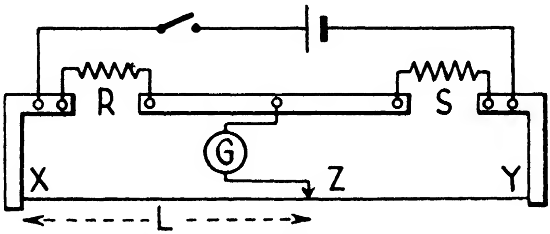

FIG. 11. THE METRE BRIDGE

is then greatest. Short, stout leads should be used for connecting R and S to the bridge, so that their unknown resistance may be negligible. It is assumed that the copper strips have negligible resistance also, and that the points where the wire is soldered to the strips are opposite the 0 and 100 marks on the scale.

The resistances of several coils should be measured, e.g. wireless coils of 100, 300, and 1000 turns. A Leclanché cell should be used with a tapping key so that it is connected only while a balance is being secured.

Experiment 9. Resistance of Wires

The resistance R of a piece of uniform wire depends upon (*a*) its length L, (*b*) its cross-sectional area A, and (*c*) the specific resistance s of the material. R is proportional to L and s, but inversely proportional to A and is given by the formula

$$R = s \cdot \frac{L}{A}$$

If d is the diameter of the wire, $A = \frac{\pi d^2}{4}$ and hence

$$R = s \cdot \frac{4L}{\pi d^2}$$

Thus, if we have two wires of the same length and material, but of different diameters, d_1 and d_2, their resistances R_1 and R_2 are in the inverse ratio of the squares of their diameters, or

$$\frac{R_1}{R_2} = \left(\frac{d_2}{d_1}\right)^2$$

Also, if we measure the resistance of a wire of known length and diameter, the value of the specific resistance can be calculated from the relation given above, from which

$$s = \frac{R \times \pi d^2}{4L}$$

The experimental work consists of two parts, first to confirm the dependence on diameter, and secondly to determine the specific resistance of various materials. The metre-bridge circuit of Fig. 11 is used with the (bare) wire under test connected in the gap R. The standard resistance S will be 1 Ω or 10 Ω, according to the value of R, being chosen so that when a reasonable length of wire is used, the balance point is near the middle of the bridge wire. Suitable wires are Nos. 22 and 30 S.W.G. eureka. Taking one of these wires about 1 metre long, measure with a micrometer screw gauge its diameter (in millimetres) at eight or ten points along its length. Allowance must be made for the zero error of the micrometer. The mean diameter is found and used in the calculations. The wire is then inserted under the terminals of the bridge gap, and the length between the terminals is adjusted until the balance point is somewhere near the centre of the bridge wire. After finding the balance point carefully, the wire is bent up at the points where it leaves the terminals, removed from the gap, and its length (between the bends) measured. The resistance of the wire is worked out from the metre-bridge formula (Experiment 8) and then the resistance per metre length is calculated.

Similar measurements are made with the second eureka wire, giving its resistance per metre length.

In order to confirm the law of dependence on diameter in the case of wires of the same length and material, the ratio of R_1 to R_2, these being the resistances per metre, is calculated and compared with the ratio of d_2^2 to d_1^2. As an example of

the agreement to be expected, the following figures are taken from the results of an experiment—

$$\frac{d_2(\text{diam. No. 22})}{d_1(\text{diam. No. 30})} = \frac{0\cdot712}{0\cdot315} = 2\cdot26$$

$$\left(\frac{d_2}{d_1}\right)^2 = (2\cdot26)^2 = 5\cdot10$$

$$\frac{R_1(1 \text{ metre No. 30})}{R_2(1 \text{ metre No. 22})} = \frac{6\cdot08}{1\cdot18} = 5\cdot14$$

The specific resistance s is calculated from the formula given by inserting the measured values of R, L, and d for the wire. Care must be taken to express both L and d in cm. The value of s for eureka will be found to be about 47×10^{-6} ohm. cm., or 47 microhm. cm.

Measurements should also be made with copper wire and its specific resistance determined. It will be found to be about 1·7 microhm. cm. A suitable gauge in this case is No. 34 or 36 S.W.G.

Experiment 10. The Lead-acid Cell

The purpose of this experiment is to examine the changes which occur when a simple accumulator, made by immersing two lead plates in a dilute solution of sulphuric acid, is charged and discharged. Although the cell so formed is of little value as an accumulator, the information gained is of importance in connexion with the charging and care of accumulators and, moreover, the changes can be observed in a reasonably short period of time.

(*a*) Two clean plates of lead with terminals free from corrosion, are set up in a jar about three-quarters full of battery acid (specific gravity about 1·20). This cell is to be charged by passing current through it from a 4-volt battery, the value of the current being controlled by a rheostat ($0 - 25\,\Omega$). Across the cell is connected a voltmeter (0–3 or 0–5 volts range) to measure the p.d. as charging proceeds. The circuit is shown in Fig. 12 (*a*). Before the switch is closed, the voltmeter should read zero.

Commencing with the smallest current, the switch is closed and observations are made of the reading of the voltmeter at definite intervals of time, say every 15 seconds. It will be seen that the voltmeter reading rises somewhat slowly to

a maximum. When this has been reached, the current should be increased until the voltmeter reads 2·6 volts and the charging continued for about 20 minutes. The changes which occur in the plates will then be obvious; the positive plate is

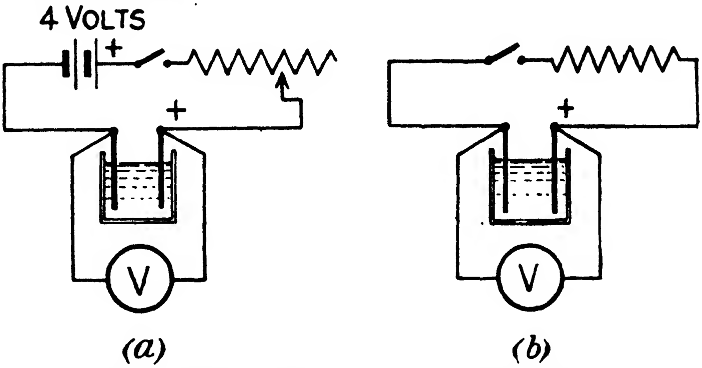

FIG. 12. SIMPLE LEAD CELL: (*a*) CHARGING CIRCUIT (*b*) DISCHARGING CIRCUIT

covered with a brown layer of lead peroxide, while the negative plate remains lead of a slate-grey colour. The circuit should be broken after charging and the voltmeter reading again observed.

(*b*) In order to discharge the cell, the charging battery is disconnected and the circuit reconnected as shown in Fig. 12 (*b*) with the rheostat resistance at maximum. Switching

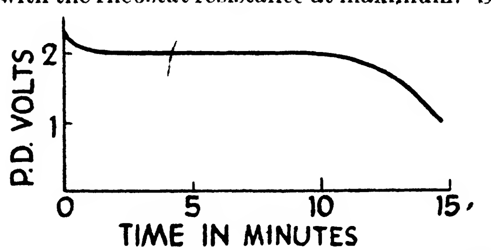

FIG. 13. CHANGE OF P.D. ACROSS LEAD CELL DURING DISCHARGE

on, the voltmeter reading is taken at one-minute intervals until it has fallen to about 1 volt. A graph may now be plotted, as in Fig. 13, showing how the p.d. across the cell varies with time during discharge.

It will be noted that for the greater part of the discharge, the p.d. remains practically constant at about 2 volts. In practice, a lead accumulator should never be discharged below 1·8 volts.

Experiment 11. Charging and Testing Lead-acid Accumulators

The proper charging and care of accumulators is of great importance in any electrical laboratory. With careful attention in both charging and discharging, a lead accumulator will last a good number of years. It can, however, be seriously damaged by neglect or by discharging at too great a rate. Regular tests of accumulators are thus very essential, the two usual tests being (i) by voltmeter, (ii) by hydrometer.

(*a*) TESTING ACCUMULATORS

Although a common voltmeter test to decide whether a cell requires recharging consists in measuring the E.M.F. in the ordinary way to see whether it is in the region of 1·8 volts, the proper way to carry out such a test is to measure the p.d. at the terminals of the cell when it is discharging at its maximum permissible rate. The maximum permissible current is either given on the label of the cell, or is found by dividing the capacity of the accumulator in ampere-hours by ten. Thus, in order to test the state of an accumulator in this way, it should be connected to a rheostat of, say, 8 Ω, capable of carrying 5 amps. with an ammeter of range 0–5 amps. in series. The rheostat is adjusted until the maximum permissible current is obtained, when the p.d. across the cell should be measured. If it is found to be 1·8 volts or less, the cell requires charging.

Measurements of the specific gravity of the acid, using a hydrometer, afford the best test of the state of an accumulator, provided the cell has originally been filled with acid of the correct specific gravity, and has received proper attention as regards its acid level at each charge. The values of specific gravity at full charge, and in the discharged state, vary somewhat with the make of cell, but it may be taken as a working rule, in the absence of other figures, that when an accumulator is fully charged, the S.G. of its acid is 1·250 to 1·270, while if the value has fallen to 1·150 to 1·170, the cell requires recharging.

An approximate idea of the state of an accumulator can be obtained by examining the colour of its plates, if they are

visible. When fully charged, the positives are a dark chocolate-brown, and the negatives are slate-grey in colour. As discharge proceeds, both plates tend to become lighter in colour.

(*b*) Charging Accumulators

Before charging, the cells should be examined and tested in one of the ways mentioned above. Even if the test shows that the cells are only partially discharged, it is still good

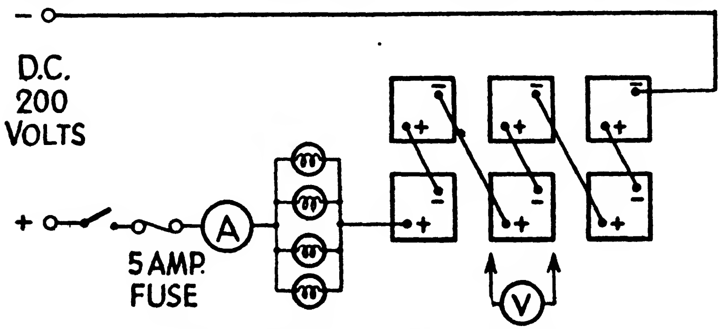

Fig. 14. Accumulator Charging Circuit

practice to charge them, as an accumulator is kept in good condition by being charged regularly (say once a week or fortnight). The charging supply will usually be the D.C. mains, and it will therefore be necessary to have a resistance in series which can be adjusted to give the correct charging current. If a suitable rheostat (60 Ω carrying 10 amps.) is not available, a good substitute consists of a number of electric lamps in parallel. Lamp sockets are wired in parallel on a board, and 50-c.p. carbon lamps or 100-watt metal filament lamps are inserted as required. The circuit is shown in Fig. 14. It contains a 5-amp. fuse, an ammeter (0–5 amps.), the parallel arrangement of lamps and the accumulators to be charged, in series, the positive pole of the supply being connected to the positive terminal of the battery. In order to avoid the danger of accidental shorting between an accumulator at the beginning and one at the end, a long insulated negative lead is used. When space limitations require the cells to be arranged in several rows (or banks), the long negative lead is still used and the correct arrangement of wiring is that shown in the diagram. With this arrangement

the p.d. between adjacent accumulators is not greater than 4 volts. Before commencing to charge, note the acid level in each cell. If it is low, owing to evaporation, add *distilled water* to bring the level up to the mark, which is usually about ¼ in. above the plates. Switching on the mains, the current is adjusted by inserting lamps in the sockets until it is approximately the correct charging value for the cells. If this is not possible, a value near 2 amps. will be suitable, in which case the charging may take longer. After several hours' charging, the individual cells should be tested by tapping the voltmeter V (0–3 volts) across each cell, and by measuring with a hydrometer the S.G. of the acid. Charging should be continued until the voltage on charge shows a constant value (generally about 2·6 volts) for one hour, or until the S.G. remains at a constant value (generally 1·270) for the same period of time. It should be noted that when the cells are fully charged, bubbles of gas are seen rising from the plates. The gas above the plates is an explosive mixture of hydrogen and oxygen; it is therefore essential to ventilate freely any room used for charging, and on no account must naked lights be used to examine the cells, or to take voltmeter or hydrometer readings. When the cells have been fully charged, they are removed from the circuit, their tops are cleaned, and the terminals smeared with a little vaseline to prevent corrosion.

(c) To Test the Capacity of an Accumulator

The capacity of an accumulator is the total quantity of electricity, measured in ampere-hours, which may be obtained by discharging (to 1·8 volts) a fully-charged cell, provided the current taken does not exceed that given by the rating of the accumulator. This rating is generally the 10-hour rate, which means that the cell is not designed to give a current greater than that which would discharge it in 10 hours.

In order to measure the capacity it is, therefore, necessary to take a fully-charged cell and to put it on load at a current given by its 10-hour rate. The time in hours for the p.d. on load to fall to 1·8 volts is measured. Then the capacity is obtained by multiplying the current in amps. by the time in hours. The capacity of an accumulator depends to some extent on the rate at which it is discharged, being greater if only small currents are taken.

Experiment 12. The Heating Effect of Current

In passing from a point of higher potential to one of lower potential, an electric current gives up energy. If there is a p.d. of V volts between two points in a circuit in which the current is I amps., then energy is expended in that part of the circuit at a rate which is given by $V \times I$ watts. This is a measure of the *power*.

If the portion of the circuit concerned is a resistance R, then $V \times I = I^2R$ (by Ohm's Law) and the energy appears

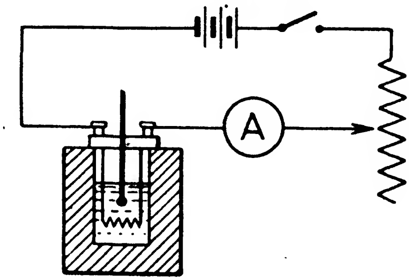

FIG. 15. HEATING EFFECT OF A CURRENT

as heat in the resistance. Thus the rate at which heat is produced by the current is proportional to the square of the current, or $H = k \cdot I^2$ where k is some constant. This means that if the current is doubled, heat is produced at four times the former rate.

In order to confirm this law experimentally, a resistance coil of eureka or nichrome is immersed in water contained in a copper calorimeter, and the rise of temperature produced in a fixed time is measured for various values of the current. Provided the mass of water used and the time taken are the same in each experiment, the heat produced by the current in the coil (and communicated to the water and container) is proportional to the rise of temperature.

A correction has to be applied to the observed rise of temperature in the manner described below, in order to make allowance for the heat which is lost by cooling while the experiment is proceeding. This cooling is considerably reduced by surrounding the calorimeter with a layer of felt.

The circuit, shown in Fig. 15, consists of the coil in series with an ammeter (0–5 amps.), a controlling rheostat of about

5 Ω, a switch and a 6-volt battery of accumulators. In addition to the coil, there is immersed in the water the bulb of a thermometer held in the centre of the lid, which also carries the terminals and thick leads to the coil. A stirrer, which consists of a loop of wire nearly fitting the calorimeter and moved up and down by a stiff wire which passes through a hole in the lid, is also required. Before taking any temperature readings, the water should be stirred to ensure a uniform temperature throughout. Having set up the apparatus, with the calorimeter about half-full, the current is switched on, quickly adjusted to 1 amp., and immediately switched off. The first experiment may now be commenced. After stirring, the initial temperature of the water is carefully read and then, at a definite instant of time which is noted on a stop-clock, the current is switched on. A constant current, adjusted at intervals as may be necessary, is allowed to flow for 20 minutes, measured on the stop-clock. During this period, the water is stirred occasionally (and especially just before switching off) and then the thermometer is read at the instant of switching off. In order to correct for the heat lost by cooling during the 20 minutes, a third reading of the temperature is taken at the end of a further 10 minutes. By adding the drop in temperature in this 10 minutes to the rise recorded in the previous 20 minutes, we get the temperature rise which would have occurred in the main experiment if there had been no cooling.

A second experiment with the same procedure is now to be carried out with a current twice as large. Keeping the same mass of water, the current is quickly adjusted to 2 amps. (or to a near value, which is measured on the ammeter) and switched off. Proceeding then in exactly the same way as in the first experiment, but with a current of 2 amps., the observed rise in temperature in 20 minutes is corrected (by observing again the fall after a further 10 minutes) to give the rise which would have occurred if there had been no cooling.

Two ratios are now worked out. First, the ratio

$$\frac{\text{Rise of temp. with 2 amps.}}{\text{Rise of temp. with 1 amp.}}$$

using, of course, the corrected figures, and secondly, $\frac{I_2^2}{I_1^2}$, which is the ratio of the squares of the two currents. If the currents

are as stated, this second ratio will be equal to four and the ratio of the temperature rises will be found to be very nearly equal to it, thus confirming the law that the heating effect of a current is proportional to the square of that current.

Experiment 13. The Internal Resistance of a Cell

The maximum current which can be given by a cell is limited by the internal resistance of the cell. Consider a cell whose E.M.F. is E and its internal resistance B arranged in the circuit shown in Fig. 16, so that it may be connected to an external resistance R by closing the switch. A voltmeter measures the p.d. at the cell terminals. When the switch is open the voltmeter reads E, the E.M.F. of the cell, since the cell is, for all practical purposes, on open circuit. When, however, the switch is closed, a current flows round the circuit and the voltmeter reading drops to V. This is the p.d. at the cell terminals on closed circuit and is less than E because the current through the cell flows from the negative pole to the positive pole and, therefore, involves a volts drop in the cell in opposition to E. This volts drop is equal to IB where I is the current, and therefore

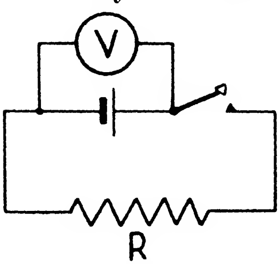

FIG. 16. DETERMINATION OF INTERNAL RESISTANCE OF A CELL

$$E - V = IB$$

But, applying Ohm's Law to the external resistance R,

$$V = IR$$

Dividing one of these equations by the other, we obtain

$$\frac{E-V}{V} = \frac{B}{R} \text{ or } B = \frac{E-V}{V} \times R$$

The value of B may therefore be found by measuring E and V for a known value of R.

It will be seen from the above theory that V will not be very different from E if B is small. A first experiment should therefore be made on a cell with considerable internal resistance, such as wet Leclanché cell. The switch in the circuit should be a tapping key, so that for small values of R the

... need not be kept running for longer than is necessary ...d V. The resistance R is taken from a resistance box and *must not be less than* 2 Ω in any of these experiments. Starting with $R = 10\ \Omega$, the open-circuit reading of the voltmeter is taken, to give E and then, closing the key, the closed-circuit reading is taken, giving V. The key is immediately released. This procedure is repeated for $R = 10$, 5 and 2 Ω in succession, the readings being tabulated and B worked out in each case. It will probably be found that B is not quite constant, but depends on the current taken from the cell, becoming slightly smaller as the current is increased.

Similar sets of observations should then be made on a dry cell and on an accumulator. It is particularly important, with these cells, to see that the circuit is closed for only a very short time, say two seconds or less. In each case, unless the dry cell is at the end of its useful life, the internal resistance will be found to be much smaller. That of the accumulator may be as small as 0·03 Ω, which is the reason for ensuring that accumulators are never short-circuited. If such a short circuit were to occur, the current would be initially equal to $\frac{2{\cdot}1}{0{\cdot}03} = 70$ amps., which would cause serious damage to the cell.

One result, which is never applied to cells, but which is useful in calculations on the equivalent circuits of wireless valves, follows from the above theory. If the source is short-circuited so that $R = 0$, then $V = 0$ and $B = \frac{E}{I}$.

Or, expressed in words—

$$\text{Internal resistance of a source} = \frac{\text{Open-circuit volts}}{\text{Short-circuit current}}$$

Experiment 14. Maximum Power in External Circuit

The power (in watts) which a source of given E.M.F. can deliver to the external circuit or load connected to it, depends on the internal resistance of the source as well as upon the resistance of the load. It can be proved that this power is a maximum if the external resistance is equal to the internal resistance, and the purpose of this experiment is to confirm this result. In a radio receiver this principle of obtaining the maximum power is applied in the circuit of the last (or power)

valve working the phones or loud speaker, the load and valve being then said to be matched.

In the present experiment an artificial resistance B is introduced between two accumulators to give an internal resistance much greater than that of the actual cells, which is negligible, and this arrangement is to be considered as the source with terminals X and Y (see Fig. 17). A 16 Ω or 25 Ω

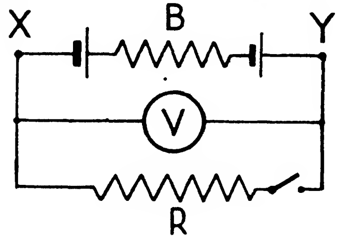

FIG. 17. CIRCUIT FOR INVESTIGATING MAXIMUM POWER IN LOAD

rheostat serves very well for B. The external load is a resistance R taken from a box, and a voltmeter V (0–5 volts) is connected across XY (it is also across R when the circuit is closed). The power expended in R is I^2R or V^2/R watts when I is measured in amps., V in volts, and R in ohms.

Before closing the switch, the voltmeter reading should be taken to give E, the E.M.F. of the source. Then setting $R = 0, 1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 20, 30, 50, 70\ \Omega$ in turn, and closing the switch, the voltmeter reading V is observed for each value of R. When $R = 0$, the value of V should be 0. If it is not so, the contacts of the resistance box are loose or require cleaning, a point which should always receive attention when low values of resistance are used from a resistance box.

From these readings the power W expended in R is calculated for each value of R. If these are tabulated it will be seen that, as R increases, W rises to a maximum and then decreases. By plotting W against R, the value of R at which the maximum occurs may be found. Such a graph will have the form shown in Fig. 18.

In order to confirm that the maximum occurs when $R = B$, it is necessary to measure B, as the actual resistance of the rheostat may be different from its nominal value. To do this,

adjust R until $V = \frac{1}{2}E$. Then B is equal to this particular value of R.

A second experiment may be carried out using a different

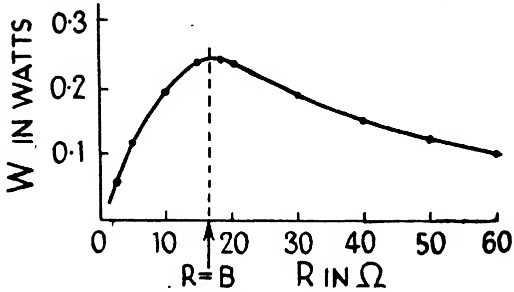

FIG. 18. RELATION BETWEEN POWER W AND LOAD RESISTANCE R

rheostat, say 25 Ω, for B. It will be found again that the maximum power in R occurs when $R = B$.

Experiment 15. Voltmeter Resistance

It has already been pointed out (see Experiments 4 and 7) that when measuring the p.d. between two points in a circuit by means of a voltmeter, the resistance of the instrument used is an important consideration. It should be clearly realized that a voltmeter, *when connected in a circuit*, records the p.d. between its terminals. The reading obtained will depend on the components of the circuit and on the resistance of the voltmeter. This will be illustrated by the tests to be made in these experiments. Two voltmeters of about the same range (say 0–3 volts) will be required, one having a low resistance, perhaps 300 to 450 Ω, and the other a high resistance, perhaps 3000 Ω.

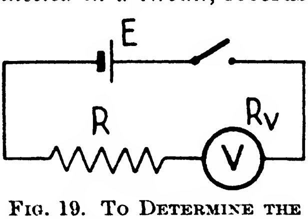

FIG. 19. TO DETERMINE THE RESISTANCE OF A VOLTMETER

(*a*) DETERMINATION OF THE RESISTANCE OF A VOLTMETER

The low resistance voltmeter is connected in series with a 2-volt accumulator, a resistance box and a switch as shown in Fig. 19. Let R_v be the resistance of the voltmeter and R

the resistance in the box. Then the p.d. across the voltmeter will be $V = \frac{R_v}{R + R_v} \times E$ (since the internal resistance of the cell is negligible) and the instrument will record this voltage. It should be noted (i) that if $R = 0$, then $V = E$, (ii) that if $R = R_v$, then $V = \frac{1}{2}E$, which gives a simple method of

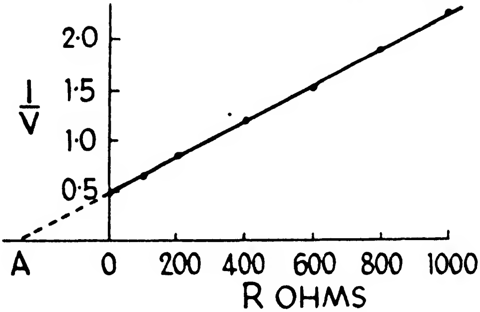

FIG. 20. RELATION BETWEEN R AND $1/V$

measuring R_v, viz. by adding R to the circuit until the voltmeter reading is one-half the E.M.F. of the cell, and (iii) that the equation may be written $R + R_v = \frac{R_v \times E}{V}$, which enables corresponding readings of R and V to be dealt with by a graphical method.

Commencing with $R = 2000\ \Omega$ and setting it in turn at 1000, 800, 600, . . . 100, 0 Ω, the voltmeter reading at each resistance is observed and recorded. In order to treat the observations graphically, $1/V$ is worked out and plotted against R. This should give a straight line, which if produced backwards, as shown in Fig. 20, cuts the axis of R at a point A such that the intercept OA gives the resistance of the voltmeter. As a check on the result, the value should be found by the method indicated in (ii) above, in which R is adjusted until $V = \frac{1}{2}E$.

(*b*) P.D. MEASUREMENTS IN A SIMPLE CIRCUIT

A 2-volt accumulator is connected to two resistances P and Q taken from boxes in series. Across Q are connected two voltmeters, each with a key so that either or both may be used. V_1 is the low resistance instrument whose resistance

R_v has been measured, while V_2 is a high-resistance instrument of about the same range (0–3 volts). P and Q are each set equal to R_v. First connect only V_1 to the terminals of Q, and observe its reading (although $P = Q$, *it is not* 1 *volt*). The reading of V_1 is that which would be expected for the p.d. across Q with V_1 connected to it, and this value should be

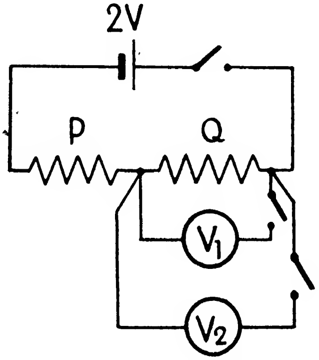

FIG. 21. USING VOLTMETERS OF DIFFERENT RESISTANCE

checked by calculation from the known values of P, Q, and R_v. Secondly, connect V_2, as well as V_1, across Q. It will be seen that there is no appreciable change in the reading of V_1 and that V_2 reads the same as V_1 within instrumental error. Thus V_2 does record without appreciable error, owing to its high resistance, the p.d. already existing between the two points to which it is connected. Thirdly, disconnect V_1 and observe the reading of V_2 alone connected across Q. It may then be checked by calculation that this is very nearly the p.d. existing across Q before V_2 was connected.

Strictly, the connexion of any instrument which takes current disturbs the circuit, but with a high-resistance instrument the effect is negligible. The ideal instrument for measuring p.d. would be a voltmeter which took no current; the electrostatic voltmeter is such an instrument, but it is insensitive at values less than 50 volts.

CHAPTER II

MAGNETISM AND ELECTROMAGNETISM

In this chapter the experimental work is concerned with the basic facts and principles of magnetism and electromagnetism and with some of their applications.

Experiment 16. Lines of Magnetic Force

When a bar of steel is magnetized, its magnetism is most apparent in regions near the ends, which are called the poles. If the magnet is hung up horizontally in a stirrup and allowed to come to rest, the pole which points towards the north is called the North pole, while the other is the South pole. Magnetic poles attract or repel one another according to their kind. Like poles repel and unlike poles attract each other. These forces of repulsion or attraction are explained by means of lines of force which are found in the neighbourhood of a magnet and, in fact, wherever there is a magnetic field. They leave a magnet at the North pole and enter it at the South pole. They are in a state of tension along their length and act as if they repelled each other laterally.

The distribution of the lines of force round a magnet may be investigated (*a*) by iron filings, (*b*) by plotting with a small compass needle.

(*a*) Iron Filings Method

The filings are contained in a small canister with a wire gauze top, through which they may be sprinkled on to a sheet of card about 12 in. × 8 in. The layer of filings should be even, but not too thick.

(i) *A Single Bar Magnet.* The card with its layer of filings is carefully placed over the magnet, which should be at the centre, and the card is gently tapped. Each filing becomes a small magnet which sets itself along the line of force at the point where it is. A sketch should be made of the lines, it being remembered that the lines are actually unbroken curves, which never intersect. The direction of the field along each line should be indicated by arrows, showing the direction in which a very small North pole would travel.

A permanent record of the disposition of the filings may be obtained by using blue-print paper, or photographic paper

in place of the card, the paper being developed and fixed in the normal way after exposure to light.

(ii) *Two Magnets in Line.* The magnetic field between two unlike or two like poles may be mapped out in a similar way. Two bar magnets are placed in line, first with unlike poles and secondly with like poles facing each other about 2 in. apart. The field is investigated by filings. In the first case, it will be seen that the lines from the North pole of one magnet

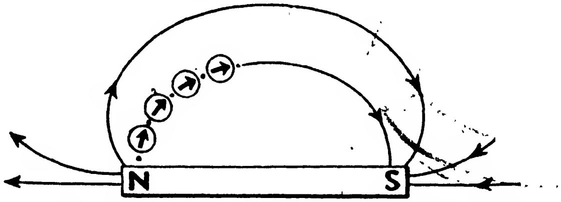

FIG. 22. PLOTTING LINES OF FORCE BY COMPASS NEEDLE

pass to the South pole of the other magnet, and, if the card is tapped, the filings move as if the lines were trying to shorten themselves. This provides the explanation of the attraction between unlike poles. In the second case, the lines from the similar poles turn aside from each other and, if the card is tapped, the filings move away from a point between the poles. The lines of force repel each other sideways and thus give the repulsion between like poles.

(iii) *The Effect of Introducing Soft Iron into the Field.* A piece of iron sheet about 2 in. × 1 in. is placed at the centre of the space between two magnets arranged in line with unlike poles towards the iron, and the lines of force are mapped out by filings. It will be found that the lines bend into the iron, and the iron becomes magnetized by induction. Where the lines enter the iron there is induced a South pole, and where they leave there is induced a North pole.

(*b*) COMPASS NEEDLE METHOD

Lines of force may be plotted by using a small compass needle in the following way. Place the compass on the paper and mark by dots on the paper the position of the ends *A* and *B* of the needle. Now move the compass until the end *A* covers the dot originally under *B* and mark the new position of the end *B*. Continue in this way and draw the line joining the dots to give the line of force. This is illustrated in Fig. 22.

The method should be applied to those cases already studied by the filings method, drawing out some 15 to 20 lines in the important regions of the field. In the cases involving two magnets, these should be set further apart than for the experiments with filings. As before, it is important to indicate the directions of the lines of force.

Experiment 17. Magnetic Field Due to a Current

The discovery, by Oersted, that an electric current has a magnetic field associated with it, is of fundamental importance.

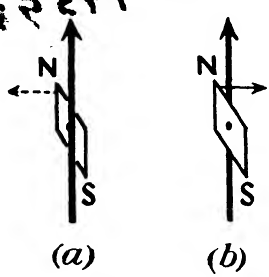

FIG. 23. DIRECTION OF MAGNETIC FIELD DUE TO A STRAIGHT CURRENT
(a) BELOW THE WIRE
(b) ABOVE THE WIRE

If a compass needle is placed near a straight wire, it is found to be deflected when a current is passing through the wire. The direction of this magnetic field, is given by Ampère's swimmer's rule, or by Maxwell's right-hand screw rule. The former states: Swim with the current, facing the compass needle, then the North pole will move to the left, thus giving the direction of the magnetic field. The latter states that the lines of magnetic force are circles round the wire, and that the direction of the field along these lines is the direction of rotation of a right-handed screw turned so as to travel in the direction of the current.

The strength of the field is proportional to the current and inversely proportional to the distance from the wire.

(a) THE FIELD DUE TO A STRAIGHT CURRENT

A 2-volt cell is connected, through a switch, to a length of about ½ metre of No. 30 S.W.G. eureka wire (this avoids the use of a rheostat which, unless specially wound, would give a field itself). A good portion of the wire is held parallel to a compass needle set near the wire. Switching on the current, the direction of motion of the North pole of the compass is observed first when the wire is above the needle, and secondly when it is below. Knowing the direction of the current, the rules given above for the direction of the magnetic field are confirmed (see Fig. 23). In a further experiment, the

wire should be held vertically, passing through the centre of a stiff card or piece of wood held horizontally. The compass needle is placed on the card and moved round the wire, when it will be found that the lines of force encircle the wire, with direction given by the right-hand screw rule. They will not be circles, however, since the magnetic field of the earth will cause some distortion.

(*b*) The Field Due to Current in a Helix

A suitable helix for this experiment is one made by winding insulated copper wire No. 24 S.W.G. on an ebonite or paxolin

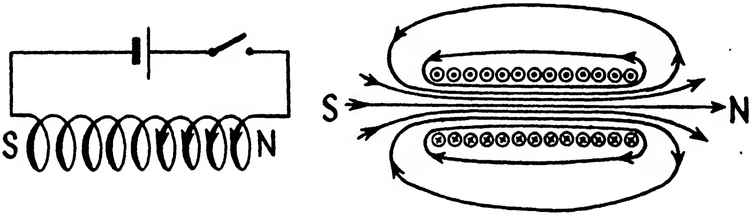

Fig. 24. Magnetic Field due to Current in a Helix

tube about $1\frac{1}{2}$ in. in diameter and 8 in. long. The wire, which should be close-wound, may be in several layers, provided the direction of winding is the same in each layer. The helix is set along the magnetic E.–W. line and is connected to a 2-volt accumulator and a switch. The magnetic field inside and near the ends of the coil may be investigated by filings or by compass needle. A piece of card is cut so that part of it can slide inside the tube along a central plane while the remainder, which is wider, stands outside. Filings are sprinkled uniformly on this card, which is then inserted and the current switched on. After tapping and switching off, the card is carefully removed and a diagram drawn showing the disposition of the lines of force. It will be noted that the lines are parallel within the helix, denoting a uniform field.

A compass needle may also be used to plot some of the lines. In this case, the lines should be followed back along the outside of the solenoid and their direction noted. It will be seen that they emerge from one end and enter the other end of the coil, thus giving it polarity like a magnet. The right-hand screw rule may now be applied (see Fig. 24) to

confirm the polarity. Alternatively, if the direction of winding is unknown, it may be found by testing the polarity. It should also be noted that the lines of force are closed curves, passing through the coil and back round the outside.

(c) The Effect of an Iron Core

For this experiment a helix of smaller diameter is desirable so that a soft-iron bar or bundle of iron wires of reasonable size may be inserted to fit. Placing the compass needle at about 10 cm. from the end of the coil, the large increase in the strength of the field there due to inserting a soft-iron core in the solenoid may be shown by noting the much more rapid rate of vibration of the needle as it settles to its final position. The polarity of the iron agrees with that of the helix alone. Moving the needle near the end of the iron bar, it will be seen that the bar has become temporarily a strong magnet. The current is now switched off, when it will be found that the magnetization of the iron has dropped almost, but not quite, to zero. This is due to the demagnetizing action of the reverse field set up by the poles induced in the iron.

(d) Field Due to a Current in a Circular Coil

Another important case in which the field may be investigated is that of a flat circular coil. Such a coil, consisting of 200 to 500 turns wound on a former whose mean diameter is, say, 15 cm., can be fixed with its plane vertical in the middle of a horizontal board which passes through the centre of the coil (the board consists of two parts, cut so as to accommodate the coil and fixed together again). With a sheet of paper on the board in the neighbourhood of the coil, the magnetic field due to a current in the coil is plotted with a compass needle. The lines of force are again closed curves, not exact circles, which ring the conductor. The strength of the field depends upon the number of ampere-turns, i.e. the current in amps. $\times$ the number of turns. If the coil has 500 turns of resistance 10 Ω and is connected to a 2-volt cell, then the current is 0·2 amp. and the ampere-turns are equal to 100.

In all the above experiments it should be noted that the lines of force are closed curves linked with a conductor, and when the current is cut off the lines collapse and in so doing

cut the conductor. This gives electro-magnetic induction, which is the subject of the following experiments.

Experiment 18. Electromagnetic Induction—The Laws of Faraday and Lenz

Electromagnetic induction occurs when a conductor is moved so as to cut a magnetic field or when a magnetic field linked with a conductor is changing. Under these circumstances an E.M.F. is induced in the conductor. This principle has many applications, as in the dynamo and the transformer. *Faraday's Law* states that the magnitude of the induced E.M.F. depends on the *rate of cutting* of the lines (or the *rate of change* of the number of linkages) and is proportional to this rate. *Lenz's Law* states that the induced E.M.F. is set up in such a direction that the effect of the induced current tends to oppose the change which produces it.

The present experiments are intended to illustrate these laws. A bobbin with a hole through the centre large enough to take a bar magnet freely, carries two independent coils of the same size and number of turns (say 20 turns each). The direction of winding of each coil must be known, and, if not obvious, should be marked by arrows on the outside when the coils are made.

(*a*) To Observe the Induced Effect and to Show that it Depends on the Rate at which the Magnetic Field Changes

One coil is connected to a sensitive galvanometer and then one pole of a bar magnet is inserted into the coil. The galvanometer will give a kick, showing that a momentary current has passed through it. The direction of the kick should be noted and also that there is no movement of the galvanometer when the magnet is stationary, even within the coil. Then the pole is withdrawn and it will be seen that there is a kick in the direction opposite to the first. This experiment should then be repeated, using (i) a very slow movement of the magnet, and (ii) a rapid movement of the magnet. The difference in the effect in these two cases will show that the induced effect is greatest when the field changes at the greatest rate. The best results are obtained by withdrawing the magnet from the coil.

(*b*) To Show that the Induced Effect is Proportional to the Number of Turns on the Coil, for the Same Rate of Change of the Magnetic Field

The two coils on the bobbin are connected in series so that their windings are in the same direction and then to the galvanometer. Placing the magnet with one pole inside the coil, the galvanometer zero is observed, and then the kick when the magnet is suddenly withdrawn. The mean of several observations should be taken. The mean throw of the galvanometer should be compared with that obtained with the same magnet when only one of the coils is used. It should be twice as large.

(*c*) To Make a Non-inductive Coil

The two coils on the bobbin are now connected so that their windings are in opposition. Changing the field suddenly as before, it will be found that no appreciable effect can be observed on the galvanometer.

The coils of resistance boxes are wound non-inductively by doubling the wire on itself before winding and then winding the double strand as one.

(*d*) To Confirm Lenz's Law

In order to confirm this law (given above) it will be necessary first to determine which way the current flows through the galvanometer when the deflexion is in a known direction, say to the right. A 4-volt battery is connected in series with a resistance of 1 megohm and the galvanometer. This will give a current of about 4 microamps., the direction of which is known from the polarity of the cell, and this current will usually be sufficient to cause a slight deflexion of the galvanometer. Should the galvanometer be insensitive, a lower resistance, say 50,000 Ω, may be used.

Then, returning to the single coil connected to the galvanometer, the direction of the induced current when the North pole of the magnet is brought up to one face is observed. By Lenz's Law it should be in such a direction as to produce a retarding field, i.e. a North pole on that face of the coil.

Looking at the coil face, a clockwise current produces a South pole and an anti-clockwise current produces a North pole. Thus, as the direction of winding is known, the law can be checked. Further observations should be made with

the North pole moving out, and with the South pole moving in and moving out. Diagrams similar to Fig. 25 should be drawn for each case.

In the above experiment (except part of section (*a*)) and in that which follows, the change in the magnetic field is made in a time which is short compared with the period of swing of the galvanometer. Using this simple apparatus, it is not possible to measure either the induced E.M.F. or the rate of change of the magnetic field. The galvanometer, when used as described, gives a throw which is very nearly proportional to the total change in the number of linkages with the coil connected to it.

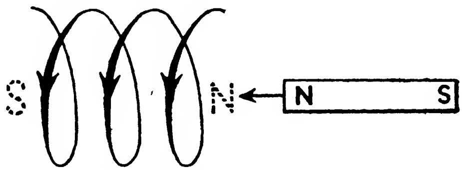

FIG. 25. TO CONFIRM LENZ'S LAW

Experiment 19. A Second Experiment on Electromagnetic Induction

In the last experiment the change of field was produced by moving a magnet. The change may also be produced by altering the current in a coil (called the primary) near which another coil (called the secondary) is situated. An E.M.F. will be induced in the secondary and the effect is governed by the laws of Faraday and Lenz when applied to this coil.

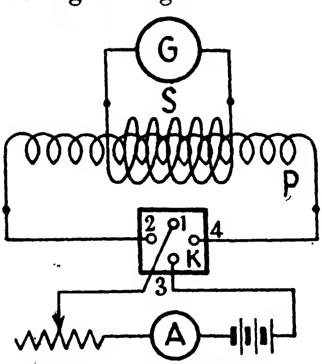

FIG. 26. ELECTROMAGNETIC INDUCTION USING PRIMARY AND SECONDARY COILS

A convenient primary coil consists of a solenoid about 30 cm. long, wound with some 900 turns of No. 22 S.W.G. copper wire. The secondary is a coil of 200 turns with a tapping at 10 turns (for a later experiment), wound on the primary, but insulated from it. The solenoid should be capable of taking an iron core when desired.

The circuit for these experiments is shown in Fig. 26.

The primary coil P is connected through a reversing switch K to a 6-volt battery, an ammeter (0–1), and a rheostat in series.

The secondary coil S of 200 turns is connected to a galvanometer. When the switch K is in the position in which its connexions are 1 to 4 and 2 to 3, the current passes through P in the direction from left to right in the diagram. If K is now switched over so that the connections are 1 to 2, and 3 to 4, the direction of the current through P is reversed. The key will probably have also a position in which the current is broken.

(a) To Observe the General Characteristics of the Induced Effect

With the current adjusted to about 0·3 amp. and having removed the iron core if present, the direction and approximate magnitude of the galvanometer throw should be observed (i) when the current is broken, (ii) when the current is made, (iii) when the current is reversed, and (iv) when it is reversed again.

The induced current changes its direction at successive reversals, while the throw for a reversal is very nearly double that for the make or break of the current.

(b) The Relation between the Induced Effect and the Current Reversed in the Primary (Core Non-magnetic)

Since the magnetic field due to a current-carrying solenoid without a magnetic core is proportional to the current, we should expect the E.M.F. induced in the secondary to be proportional to the rate of change of primary current. This will be true whether all the lines of force are linked with the secondary, as in this case, or not, provided the primary and secondary coils are fixed in position. If the change in current is made sufficiently quickly, then the galvanometer throw should be proportional to it. Setting the current at 0·1, 0·2, . . . amp. in succession, the galvanometer throw on reversal at each value is observed, the mean being taken of several observations. Then plotting the mean throw against the current, a straight line will be obtained thus confirming the deduction from Faraday's Law.

(c) TO INVESTIGATE THE EFFECT OF AN IRON CORE

If an iron core, consisting of a bundle of fine iron wires, is inserted in the solenoid, the magnetic field produced will be much greater, and with a secondary of 200 turns, the galvanometer throw would be very large. A secondary of a smaller number of turns (say ten) is therefore used. With this change, the last experiment is repeated, using reversal of approximately the same currents as before. On plotting galvanometer throw against current, it will be noted at once that, in this case, the curve is not a straight line, but begins to bend towards the axis of current as the current increases. This may be explained from the magnetization curve of iron which eventually reaches saturation. (See Experiment 20.) In order to show the relative effects of air and iron cores, the throw which would have been expected with 200 turns on the secondary should be calculated by proportion, and then the ratio $\frac{\text{Throw with iron}}{\text{Throw with air}}$ worked out at each current value used. It will be noticed that this ratio decreases as the current increases, i.e. as the iron approaches saturation.

These experiments have an important bearing on the action of a transformer, an air core being used for high-frequency, and an iron core for low-frequency alternating currents.

Experiment 20. Magnetization of Iron—The Hysteresis Loop

When a bar of iron (or steel) is magnetized by being placed in a uniform magnetic field of strength H, it attains an intensity of magnetization I which depends on H in the manner shown by the dotted curve in Fig. 28. As H is increased from zero, the magnetization rises slowly at first, then much more steeply, then more slowly again, and eventually reaches a constant or saturation value. If, after reaching saturation, the magnetizing field is decreased, the magnetization does not return along the dotted curve, but along the line AB, there being a considerable intensity of magnetization remaining when $H = 0$. The lagging of I behind H is called *hysteresis*. If now H is reversed and gradually increased in the negative direction, the curve BC is traced out, C corresponding to saturation in the opposite direction. On increasing H back to zero and then to its original positive value for saturation the curve CDA is followed. Thus, in

one cycle of magnetization, the hysteresis loop $ABCDA$ has been traced. The shape and size of the loop give important information as to the suitability of a magnetic material for any particular purpose. The area of the loop is a measure of the work which must be done when the material is taken *through a cycle of magnetization. In the case of the iron core of a transformer, the iron is being taken continuously through such cycles and the loss of energy due to hysteresis is known as the hysteresis loss and forms the greater part of the iron* loss of the transformer.

The purpose of the present experiment is to obtain the hysteresis loop for a specimen of iron in the form of a bundle of wires placed in the solenoid used in the previous experiment, and magnetized by passing measured currents through the solenoid. The intensity of magnetization is found by measuring the magnetic field on the axis of the solenoid at a short distance from it by the use of a deflexion magnetometer. This magnetometer consists of a short compass needle pivoted to swing freely in a horizontal plane at the centre of a circular scale marked in degrees. The needle carries a very light pointer fixed to it at right angles and moving over the divisions of the scale. To avoid parallax errors in reading, the base of the instrument consists of a mirror in which the reflexion of the pointer can be seen. The eye is placed so that the pointer covers its reflexion when the reading is taken. The magnetometer is first adjusted (with al other sources of magnetic field, such as iron and ammeter, removed) so that it stands on the level of the centre of the solenoid and so that its pointer reads 0. This latter adjustment is made by rotating the box, tapping it gently to overcome any friction on the pivot. If each end of the pointer does not read 0, the instrument should be set so that its mean reading is 0 and then, in any subsequent reading, the mean of the readings at each end is taken as the deflexion. When a magnetic field acts (on the compass needle) at right angles to the earth's magnetic field, the needle is deflected until it remains in equilibrium under the action of the two fields. When this is the case, the deflecting field is proportional to the tangent of the angle of deflexion θ. This deflecting field is to be that due to the magnetized iron and is proportional to the intensity of magnetization. Thus I is proportional to $\tan \theta$.

As the solenoid without its iron core will give a magnetic

field when a current passes through it, it is necessary to compensate for the field due to the solenoid by placing a small coil C of 100 to 200 turns on the side of the magnetometer opposite to the solenoid, arranging it to carry the same current as the solenoid, and placing it in a proper position for compensation before inserting the iron core. The leads connecting C to the solenoid should be of twin flex to avoid stray magnetic fields. The circuit is set up as shown in Fig. 27, the axis of the solenoid being along the 0–0 line of the

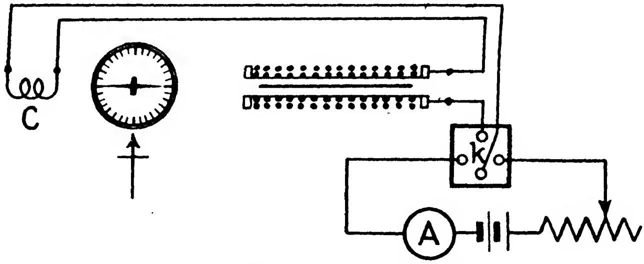

FIG. 27. MAGNETIZATION OF IRON

magnetometer, which should stand about 8 to 10 inches from the end of the solenoid. Care should be taken to keep the ammeter (0–0·5 amp.) and the rheostat well away from the magnetometer. The current is supplied by a 4-volt battery and may be reversed in solenoid and coil by the switch k.

A rheostat of 60 Ω will probably be found to be suitable. After setting up the apparatus as described, with the core removed, a current of 0·5 amp. is switched on and C is adjusted to a position (at which it must be fixed) at which the magnetometer pointer reads zero. It may be necessary to reverse the connections to C in order to obtain compensation. Switching off, the iron is inserted in the solenoid and commencing with a small current, the current is gradually increased until it is apparent, from the deflexion of the magnetometer, that saturation has been reached. Before making any further observations, the iron should be taken round the hysteresis cycle several times, so that its initial magnetic condition for the main experiment is definite. This is done by switching off, then reversing the current to give saturation in the opposite direction, then switching off, and finally reversing again to restore the current to its original value.

After several such cycles have been traversed, the main experiment may be commenced. It is important to note that, in changing the value of the current when traversing the cycle, there must be no retracing of steps to obtain a precise setting of the current; attempts should be made to proceed from any one of the current values given below to

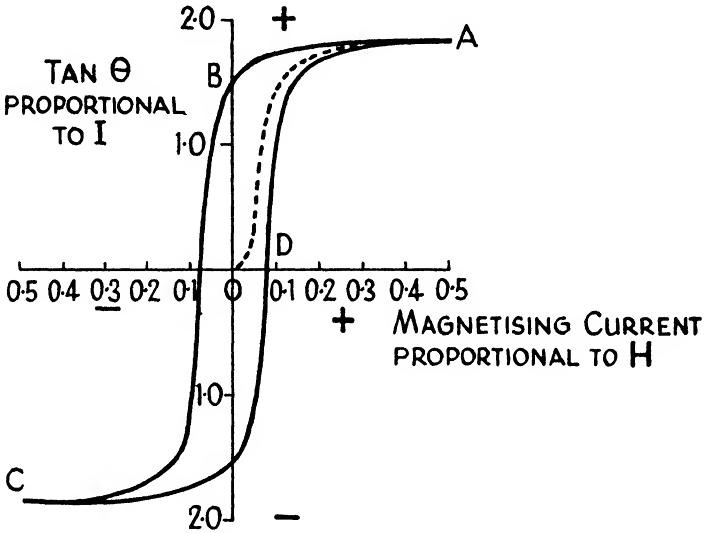

FIG. 28. HYSTERESIS LOOP FOR IRON

the next by a single movement of the rheostat slider. At each step the current is read on the ammeter, together with the pointer readings on the magnetometer. The cycle of observations is as follows, commencing with saturation in one direction which should occur when the current is 0·5 amp. with the solenoid described.

(*a*) Current decreasing (*AB* on graph). Observations of deflexion are taken at currents of 0·5, 0·3, 0·2, and 0·1 amp., and, by opening the switch, at no current.

(*b*) Current increasing in opposite direction (*BC* on graph). The switch is closed in the reverse direction and observations are taken at 0·1, 0·2, 0·3, and 0.5 amp.

(*c*) Current decreasing (*CD* on graph). The current is

reduced in the same approximate steps, viz. to 0·3, 0·2, and 0·1 amp., readings of deflexion being taken at each. The switch is opened and an observation taken at no current.

(*d*) Current increasing (*DA* on graph). The switch is closed in the original direction and readings are taken at 0·1, 0·2, 0·3, and 0·5 amp., thus completing the cycle.

From the tabulated readings of current and mean deflexion at each current, the tangents of the angles being taken, the hysteresis curve may be drawn by plotting tan θ as ordinate against the magnetizing current (to which the magnetizing field is proportional) as abscissa.

The small area of the loop, due to its steep vertical sides, should be noted, this being a characteristic of soft iron. If desired, a similar experiment may be carried out with mild steel, when the loop will be found to be larger, but will not reach such a high saturation value.

Experiment 21. The Force on a Conductor Carrying a Current in a Magnetic Field

When a conductor carrying a current is placed in a magnetic field so that the direction of the current is at right angles to the direction of the field, there is a force acting on the conductor in a direction which is at right angles to both field and current. By Fleming's left-hand rule, if the first two fingers and the thumb of the left hand are extended so as to be mutually at right angles, with the first finger in the direction of the field, and the second finger in the direction of the current, then the thumb points in the direction of the force and gives the direction of motion if the conductor is free to move. This force is proportional to (*a*) the current, (*b*) the intensity of magnetic field, and (*c*) the length of the conductor.

These results have important applications in the moving-coil instrument and in the electric motor. The purpose of the experiment is to show that the force is proportional to the current when the field is constant by the use of a motor. A shunt-wound motor with external terminals for field and armature is required for this purpose. It has its armature circuit and its field circuit in parallel across the D.C. mains (or other D.C. supply suitable for the particular machine) as shown in Fig. 29 (*a*). The armature A is in series with the motor starter, an added rheostat of 500 Ω, and an ammeter A_1(0–5).

The field coils F may also have a rheostat of 1000 Ω and an ammeter A_2(0–1) in series with them. On the end of the spindle should be fixed a pulley 3 in.–4 in. in diameter, and wide enough to carry a small belt to which weights are to be attached. The purpose of this loading is to apply a tangential force to the pulley to oppose the tangential force due to the rotation of the armature.

Before fitting up the circuit, it is advantageous to examine the construction of the motor and to make sure that the D.C.

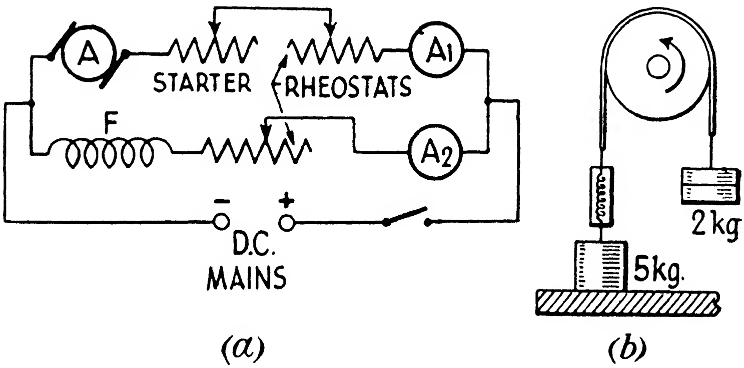

FIG. 29. (*a*) SHUNT-WOUND MOTOR CIRCUITS; (*b*) ARRANGEMENT OF PULLEY LOADING

supply is suitable for it. The values suggested for resistances and load may require considerable modification to suit a particular case.

Having connected up the circuit and set the field rheostat at its maximum value, the motor is started and the direction of rotation noted. The armature current is also observed, this being the current on no load. Switching off the current, a belt is arranged to hang over the pulley as shown in Fig. 29 (*b*), with a spring balance (0–5 kg.) hanging vertically and anchored to a heavy weight standing on the bench and with a 2-kg. weight hanging on the free end of the belt. When this arrangement has been set up, the 2-kg. weight is lifted, the motor restarted so that it takes the same no-load current, and then the weight is carefully applied to the belt over the pulley. The motor should not be started with the load on; the load should be applied as described. When the motor has

settled down, the armature current and the reading of the spring balance are observed.

The tangential force which has been applied is the hanging weight minus the spring balance reading and this is the tangential force which has been produced at the pulley by the increase in armature current. Similar measurements are now carried out with varying loads from 1 to 5 kg., care being taken that the armature current does not exceed about 1·5 amps. By plotting increase in armature current over its no-load value against tangential force, a straight line should be obtained, showing that the force on the conductors of the armature is proportional to the current. In these measurements it is essential to see that the field current remains constant.

CHAPTER III

MEASURING INSTRUMENTS: AMMETERS, VOLTMETERS, AND OHMMETERS

INSTRUMENTS are used in almost every circuit and it is, therefore, most desirable that the principles of their construction and the range of their application should be understood. Time given to examining the instruments mentioned in this chapter may be considered to be well spent.

The chief consideration, apart from range of current or voltage to be measured, is whether the measurement is of D.C. or A.C. The instrument which is invariably used for the former is the moving-coil instrument. Modern practice shows a tendency to use this instrument also, when suitably modified, for measuring A.C., particularly at high frequencies.

There are, however, other types of instrument for measuring A.C. at lower frequencies and these will also be considered from the practical point of view.

Experiment 22. Conversion of a Moving-coil Instrument into an Ammeter and into a Voltmeter (D.C.)

The essential parts of a moving-coil instrument should first be examined using an instrument with a glass front. They are: (i) a pivoted coil, which, when a current passes through it, moves round in the annular space between (ii) the hollowed pole pieces of a permanent magnet and (iii) a soft-iron core fixed centrally between the poles; the current produces a torque which turns the coil until it is balanced by the torque in (iv) the control springs of spiral shape, which also serve as leads for the current; (v) a very light pointer attached to the coil moves over (vi) a uniform scale.

Such an instrument may be converted into an ammeter of larger range by the addition of a shunt (a low resistance in parallel with the coil) or into a voltmeter by the addition of a resistance in series (sometimes called a multiplier). Before the resistances required for any particular range can be calculated, it is necessary to know the resistance of the coil and the current sensitivity of the instrument (or current for full-scale deflexion). It is assumed that the resistance G of the instrument is known.

(*a*) To Determine the Current for a known Deflexion (say 10 Divisions)

A small moving-coil galvanometer of resistance G is connected across a shunt $S = 1\,\Omega$ which is in series with a resistance box R and a 2-volt cell. Setting $R = 10{,}000\,\Omega$, the current is switched on after the zero reading has been taken, and R is adjusted until a deflexion of 10 divisions is reached. Since R is large, S is neglected in comparison when calculating

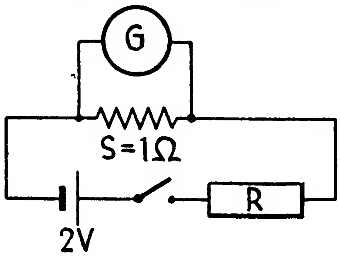

Fig. 30. To Determine the Current Sensitivity of a Moving-coil Instrument

the main current, which is therefore $2/R$ amps. Of this current a fraction $\dfrac{S}{G + S}$, or $\dfrac{1}{G + 1}$ in this case, passes through G. Hence, calculating this fraction of $2/R$ gives the current through G for 10 div. deflexion.

As an example of this calculation, the following results were obtained in an experiment: $G = 45\,\Omega$, $S = 1\,\Omega$, R for 10 div. $= 1320\,\Omega$. Hence the current through G for 10 divisions deflexion is

$$I_g = \frac{1}{46} \times \frac{2}{1320} = \frac{1}{30{,}360} = 3{\cdot}29 \times 10^{-5} \text{ amp.} = 32{\cdot}9\ \mu\text{A}$$

(*b*) To Convert the above Instrument into a Milliammeter of Range 0–10 mA for 10 Divisions

It is now required to calculate the shunt S which will give 10 divisions deflexion of G when the main current is 10 mA as shown in Fig. 31 (*a*). The main current divides into I_g ($= 32{\cdot}9\ \mu$A or $0{\cdot}033$ mA) through G and I_S ($= 10 - 0{\cdot}033 = 9{\cdot}97$ mA) through S. The voltage between X and Y is $G \times I_g$ or $S \times I_S$ and therefore $\dfrac{S}{G} = \dfrac{I_g}{I_S}$, giving, in this case, $S = \dfrac{0{\cdot}033}{9{\cdot}97} \times 45 = 0{\cdot}149\,\Omega$.

The resistance nearest to this which may be obtained from a subdivided 0–1 Ω box will probably be 0·15 Ω, or, alternatively, a piece of No. 22 eureka wire whose resistance per metre is known may be cut to give this value of S. Using the circuit of Fig. 30, connecting this shunt to the instrument and including a milliammeter of 0–20 mA range in the circuit, the value of R is adjusted until the instrument deflexion is 10 divisions, when it may be confirmed from the milliammeter

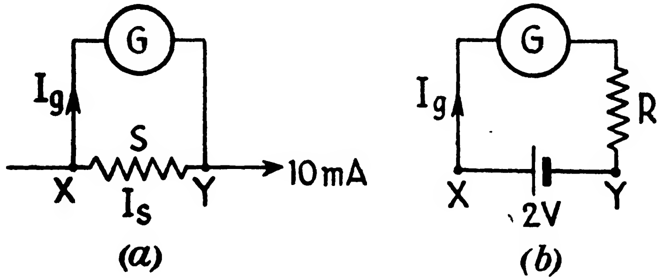

FIG. 31. (*a*) CONVERSION TO MILLIAMMETER; (*b*) CONVERSION TO VOLTMETER

reading (which is assumed to be accurate) that the main current is 10 mA. If there is any difference, the shunt will require a very small adjustment.

(*c*) TO CONVERT THE GALVANOMETER INTO A VOLTMETER OF RANGE 0–2 VOLTS (FOR 10 DIVISIONS)

For this purpose a high resistance R is required in series as shown in Fig. 31 (*b*). To calculate R, the current through G when a 2-volt cell is connected across X and Y is to be 32·9 μA. Hence, the total resistance of the circuit is, by Ohm's Law,

$$R + G = \frac{2}{32{\cdot}9 \times 10^{-6}} = 60{,}800\ \Omega$$

Hence, $R = 60{,}800 - 45 = 60{,}750\ \Omega$ approximately. Taking two wireless resistors, one of 60,000 Ω and one of 750 Ω in series, this resistance may be obtained and connected in series with the instrument. Connecting a 2-volt cell to the voltmeter so constructed, it will be seen that a deflexion of

10 divisions is obtained. The voltmeter should then be used to measure the E.M.F. of a dry cell.

Experiment 23. Examination of Various Types of Instrument

If the front covers of the instruments have to be removed in order to examine the construction, care should be taken not to damage the movements or other parts by touching them. The covers should be replaced immediately the examination is completed, in order to prevent dust, etc., from collecting inside the case.

Diagrams of the essential components of each instrument should be drawn accompanied by a statement of the types of current (or voltage) for which it may be used.

(*a*) MOVING-COIL AMMETER OR VOLTMETER

A description of these instruments has been given in the last experiment. Their scales are uniformly divided and they are used without modification only for D.C.

(*b*) MOVING-IRON AMMETER OR VOLTMETER

This instrument contains a fixed coil into which a piece of soft iron suitably pivoted and provided with a pointer and spring control is attracted. The motion is damped by a vane moving in a metal box with very small clearance, so that the pointer comes rapidly to rest with very little oscillation. As the attraction does not depend on the direction of the current, the instrument can be used for A.C. of low frequency as well as for D.C. The scale is not uniformly divided, the divisions near zero being usually very cramped.

Another type of moving-iron instrument is the repulsion type. In this, two pieces of soft iron are magnetized by the current through the coil, one being fixed and the other pivoted. Repulsion takes place between like poles induced in the iron.

(*c*) THE HOT-WIRE AMMETER OR VOLTMETER

The current, or a portion of it, passes through a horizontal wire which is stretched between terminals and kept taut by a light spring which exerts a pull vertically on the centre of the wire. The heating effect of the current causes the wire to expand and sag. A simple lever system operates a pointer attached to a small wheel and magnifies the sag. In these instruments, eddy current damping is often employed,

a small aluminium vane which is attached to the pointer moving between the poles of a small permanent magnet of such a shape that the poles are close together and thus provide a strong field. The heating effect of the current is proportional to the square of the current and therefore the instrument can be used for A.C. as well as D.C. Great care is necessary in using hot-wire and thermo-ammeters to ensure that the current is well within the range of the instrument. An overload for even a short instant of time will fuse the wire and render the instrument useless.

(*d*) THE ELECTROSTATIC VOLTMETER

A number of light vanes fixed to an axis are suspended or pivoted so that they may move between a number of fixed plates without touching, in the manner of a variable air condenser.

When a potential difference exists between the fixed and moving plates, there is a force of attraction, which depends on the square of the voltage, and the moving plates rotate until the torque due to the electrostatic attraction is balanced by that of the suspension or control spring. The instrument may be used for alternating voltage as well as for direct voltage, and has the important advantage that it takes no current with direct voltages, and an inappreciable current with alternating voltages.

The instruments listed above as suitable for A.C. measurements, together with the thermo-ammeter, which is the subject of the two following experiments, are calibrated for A.C. by using known direct currents or voltages. Their readings thus indicate the value of the direct current or voltage which would give the same effect as the alternating current or voltage measured. This is the effective, or R.M.S. value of the A.C.

Experiment 24. The Thermo-electric Couple

If two wires of different metals are connected together to form a closed circuit and one of the junctions is heated while the other remains cold, a thermo-E.M.F. is set up and a current will flow, as may be shown by inserting a galvanometer in the circuit. Two common metals for this purpose are copper and eureka, in which case the E.M.F. produced is very nearly proportional to the difference between the

temperatures of the two junctions if this temperature difference is not too large. The value of the E.M.F. is quite small, being about 50 microvolts per ° C., but it is sufficient to give a means of measuring alternating currents at all frequencies, including radio frequencies, by using a thermocouple to measure the heating effect in a wire carrying the current.

(a) To Obtain a Thermo-electric Current and to Measure the Thermo-E.M.F. per Degree Difference of Temperature between the Two Junctions

The arrangement shown in Fig. 32 is set up. Two wires of

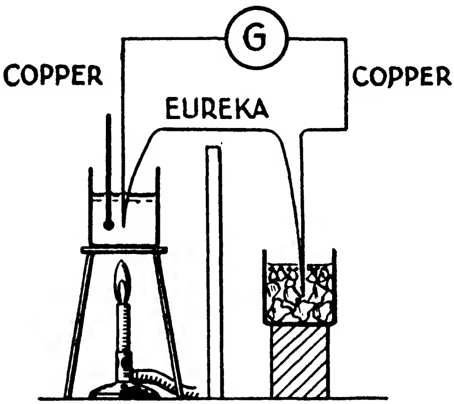

Fig. 32. Measurement of Thermo-E.M.F.

copper and one of eureka are taken, their ends are cleaned and then soldered to make two junctions as shown, the free copper leads being connected to a galvanometer. It will be advantageous if the galvanometer is that used in Experiment 22, in which its sensitivity was determined. The two junctions are placed in two beakers, one containing melting ice (0° C.) or cold water, and the other water which may be heated to various temperatures as indicated by a thermometer held in the water. If ice is not available, the temperature of the cold junction must also be measured by a thermometer. A screen is placed between the cold beaker and the bunsen to prevent the former from gaining heat by radiation.

The zero of the galvanometer is found by immersing both

junctions in the cold bath. Then, placing one junction in the water to be heated, its temperature is raised in steps, say, to about 20° C., 35° C., 50° C., and, 70° C., and, at each temperature, the galvanometer deflexion and the temperatures of hot and of cold junctions are observed. A table is drawn up showing the difference in temperature and the corresponding deflexion.

In order to deduce the thermo-E.M.F. at the galvanometer terminals, it is necessary to calibrate the galvanometer and to know its resistance. The calibration is carried out exactly as described in Experiment 22 (*a*), using the circuit of Fig. 30. If I_g microamps are required to give a deflexion of D divisions, then the current per division is $\frac{I_g}{D}$ microamps, and if the resistance of the instrument is G ohms., the p.d. at the terminals per division deflexion is $\frac{I_g \times G}{D}$ microvolts. Using this factor, the deflexions observed with the thermocouple may be converted to microvolts, and then the thermo-E.M.F. per ° C. difference of temperature can easily be calculated for each of the temperature differences used. In the above calculation, it is assumed that the resistance of the couple is negligible.

Experiment 25. Construction of a Simple Thermo-ammeter

A small board with two terminals H (for heater) and two marked G (for galvanometer) is useful for this purpose. A heater coil C is made by winding 8 in.–10 in. of No. 22 S.W.G. nichrome wire into a coil of some 10 turns of ¼ in. diameter and connected to the terminals H. This coil is to be heated by a current from a 6-volt battery with a rheostat (20 Ω) and a moving-iron ammeter (0–1) in series. A thermocouple is also made by cleaning and twisting tightly together the ends of two pieces of nichrome and eureka wires. The free ends are joined to the terminals G and the thermocouple is inserted into the centre of the coil without touching it. A galvanometer is connected to the terminals G by copper wires. When a current is passed through C, the thermo-junction becomes heated, giving a thermo-electric current through G, whose deflexion can therefore be related to the current in C.

Having set up the arrangement shown in Fig. 33, the thermo-ammeter should then be calibrated by passing various currents between 0 and 1 amp. (as measured by the moving-iron ammeter) through *C*. At each current, time is allowed for the galvanometer reading to become steady, the coil being shielded from draughts. A curve may be drawn relating deflexion to current.

As the heating effect is proportional to the square of the current, the direction of deflexion will be independent of the direction of the current in *C*. This should be checked by reversing the current. It is this fact which makes it possible to use such an instrument for measuring alternating current.

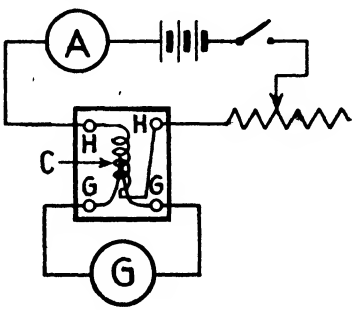

FIG. 33. SIMPLE THERMO-AMMETER

A further experiment should now be carried out using alternating current to heat the coil. An A.C. mains transformer having a 4-volt secondary should be used. The 4-volt secondary is connected in place of the battery of Fig. 33, the primary of the transformer being connected to the A.C. mains. The R.M.S. value of the current will be recorded by the moving-iron ammeter and may be adjusted by the rheostat to values between 0 and 1 amp., say 0·2, 0·5, and 0·7 amp. The galvanometer deflexions are read and it will be seen, by reference to the D.C. calibration, that they are, within experimental error, the same as for these values of direct current.

In thermo-ammeters designed to measure alternating current at radio frequencies, the heater wire and the thermocouple are very often sealed into a glass tube from which the air has been evacuated. This renders the calibration more stable and prevents contamination or oxidation of the metals.

Experiment 26. Multi-range Instruments: Ohmmeters

For many measurements in radio circuits, it is convenient to have one instrument which, by means of switches, can be used for measuring milliamperes, amperes, volts, etc., either D.C. or A.C., and of various ranges, as desired. Such instruments are of the moving-coil type in which suitable

shunts and series resistances are switched in for each range and in which alternating currents and voltages are measured by the use of small metal rectifiers. An instrument of this kind can, of course, be used only for one purpose at any one time, but its usefulness will be apparent if, for example, it is desired to measure the voltage of a H.T. battery and then

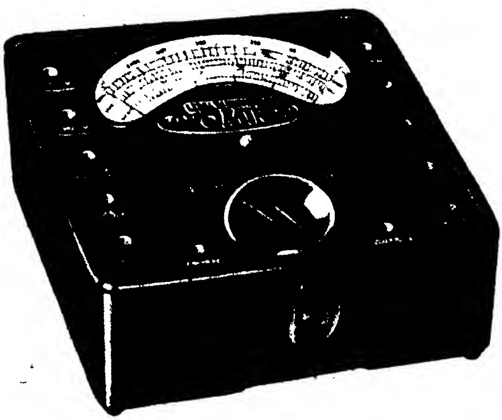

PLATE I. UNIVERSAL AVOMINOR
(*By courtesy of the Manufacturers*)

proceed to measure the current through a valve or the resistance of a component of the circuit without recourse to any other instrument. It should be regarded as a testing instrument rather than as a standard instrument.

There are usually several scales, the one on which the reading is to be made depending on the range and on the type of measurement being made. The measurement of alternating current or voltage is confined to low frequencies. Three instruments of the multi-range type in common use will be considered. Their internal circuits are too complicated to be given here, and it is unnecessary to know them, except when measuring a resistance as indicated below, where the principle of the method is described. Instructions for use are supplied with each instrument and should be carefully followed.

A small and very useful instrument of this kind is the Avominor, shown in Plate I. It provides for the measurement

of: (i) voltages up to 500 volts, both D.C. and A.C., (ii) D.C. milliamps. up to 500 mA, and (iii) resistances up to 20,000 Ω, using an internal battery and up to 10 megohms with an external battery. On the voltage ranges it has a resistance of about 400 Ω per volt. Unless an external shunt of known value is used, the instrument cannot be used for direct current above ½ amp., or for the measurement of alternating current.

The method of using the instrument as an ohmmeter is shown in Fig. 34, in which X is the resistance (up to 20,000 Ω) under test. An internal battery of 1·5 volts supplies current, which is adjustable by the variable rheostat P in the instrument, to a circuit consisting of a small resistance r, across which is the moving coil with a fixed resistance in series such that the resistance of the galvanometer circuit is about 400 Ω, not including X.

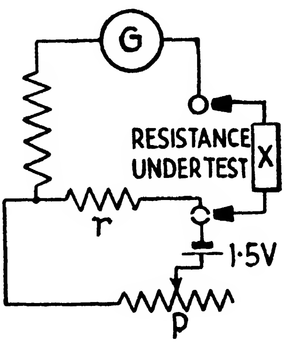

FIG. 34. MEASUREMENT OF RESISTANCE BY OHMMETER (AVOMINOR)

On inserting plugs into the two sockets shown, the dry-cell circuit is completed and then, on connecting the leads from the plugs to a resistance or shorting them, the galvanometer circuit is completed. If the leads are shorted so that the resistance between them = 0, the pointer of the instrument moves over to nearly full deflexion, and the rheostat P is adjusted until the reading is 0 on the ohms scale. The voltage drop across r is now 1 volt and it remains sufficiently near 1 volt when X is included in the galvanometer circuit, the current through G being therefore $\frac{1000}{400 + X}$ mA instead of $\frac{1000}{400} = 2{\cdot}5$ mA required for full-scale deflexion. Thus X could be calculated from the current readings, but the direct reading in ohms can be made on the ohms scale, which reads from 0 at full-scale deflexion, and which, it should be noted, is not uniformly divided. The adjustments to measure X are therefore: (i) turn switch to "Ohms"; (ii) short the leads and adjust the rheostat to bring the ohms scale reading to 0; (iii) join the leads to X, the resistance under test, and

read X on the ohms scale. No attempt must be made to measure X while current from an external source is flowing in it. Suitable resistances to measure are a 10 or 100 Ω coil from a resistance box (thus checking the instrument), a metal filament lamp, a 0–5 voltmeter, and various wireless resistors ranging from 2000 to 15,000 Ω.

The above description applies in principle to any universal instrument and the method is the same, although the number of ranges served may be greater.

Two other universal instruments which are very widely used are the Avometer and the Taylormeter. An Avometer Model 7, and a Taylormeter Model 83 are shown in Plates II and III.

The former has a large number of ranges and serves to measure both direct and alternating current and voltage, capacitance, power, and power ratio (decibels), as well as resistance, there being suitable scales for these purposes. The resistance on the voltage ranges is about 500 Ω per volt. The range desired is selected by two dials on the face of the instrument, one being for D.C. and the other for A.C. An important feature is the cut-out, which operates on a small accidental overload, thus protecting the instrument. It is not intended to act as a protection against serious overloading and care should be taken in choosing the range to be used, always selecting a higher range to begin with if in doubt. The leads are provided with alligator clips or with prods, the latter being used for testing at less easily accessible points in a circuit.

The Taylormeter is a similar instrument, although the arrangement of switching and range setting is rather different. There is no cut-out, but the instrument has the advantage of a very high resistance on the voltage ranges, approximating to 4000 Ω per volt in the model shown, and 1000 Ω per volt in another more compact model (No. 90).

In this instrument the ranges available are somewhat different from those of the Avometer, so that for certain purposes one instrument might be chosen in preference to the other. It should be noted that multi-range instruments are not usually designed for continuous loading and their internal resistances are liable to be seriously overheated or even burnt out if they are used under such conditions.

A complete description of these instruments cannot be

given in this book. Their various uses are described in the instructions issued with the instruments, and which should be carefully followed.

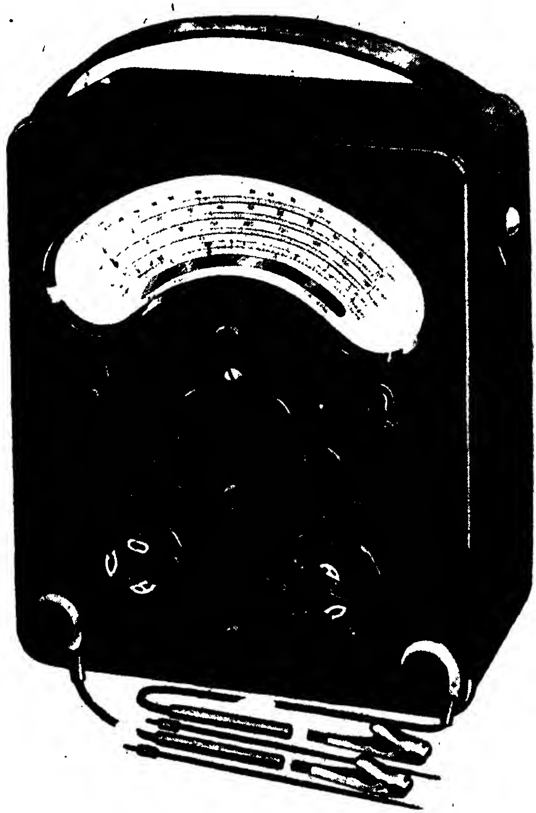

PLATE II. AVOMETER MODEL 7
(*By courtesy of the Manufacturers*)

The measurement of resistance over all ranges using an Avometer or a Taylormeter is an experiment which should be carried out after a general inspection of the instrument. The following is a description of these measurements with an

PLATE III. TAYLORMETER MODEL 83
(By courtesy of the Manufacturers)

Avometer. This instrument covers the ranges 10,000 Ω, 100,000 Ω, and 1 megohm, using internal batteries (a single dry cell for the first two and a 9-volt dry battery for the last), and 10 megohms and 40 megohms using an external source (H.T. battery or D.C. mains). On the face of the instrument are knobs R, P, and Q which control internal rheostats for the zero ohms adjustment.

(*a*) For the first two ranges mentioned, selected by the dial switch, the leads are shorted and the reading brought to 0 on the ohms scale by the use of knobs P and R as described on the base plate of the instrument. The leads are then connected to the resistance under test and its value read from the scale. On the 1-megohm range the zero setting is made by lifting knob Q to its upper stop and rotating it in a clockwise direction. At the conclusion of the measurements, this knob must be restored to its original position.

Measurements should be made of the resistance of a number of coils, wireless resistances, grid leaks, etc., and their resistances compared with the nominal values.

(*b*) Before using the two highest ranges, it should be ascertained that the lower resistance ranges are inadequate. Then, setting the D.C. switch on the 100-volt range, the knob Q is raised to its upper stop and an external battery (80–120 volts) is connected to the instrument. Q is rotated until the zero on the ohms scale is indicated and then the resistance X is connected in series with battery and instrument. X is found by multiplying the scale reading by 1000. The insulation resistance of a waxed paper condenser is suitable for this test. For resistances in the 40-megohm range, the 400-volt switch position is used and the supply voltage must lie between 250 and 1000 volts.

In using ohmmeters having several resistance ranges, it is a good practice to use a higher resistance range than that which will just cover the resistance to be measured, as then a larger deflexion will be obtained, giving a better reading.

CHAPTER IV

CONDENSERS

A CONDENSER consists essentially of two metal plates, insulated from each other and separated by a dielectric, which may be air, mica, paraffin wax, etc. If a charge $+Q$ is given to one plate, the other plate being earthed, a charge $-Q$ appears on the earthed plate and there is a difference of potential V between the plates. The capacitance C of such a condenser is defined as the ratio of charge on one plate to the potential difference between the plates. This is a constant for a given condenser since the potential difference is directly proportional to the charge. Thus $C = Q/V$. If Q is expressed in *coulombs* and V in *volts*, then C is expressed in *farads*. A capacitance of 1 farad is so large, however, that for practical purposes 1 *microfarad* (μF) (10^{-6} farad) is taken as the unit. This will be the capacitance of a condenser in which there is a difference of potential of 1 volt for a charge of 1 microcoulomb.

The value of C depends on the area of the plates, the dielectric constant of the medium between them and the distance apart of the plates. For a parallel plate condenser, to which most practical cases approximate very closely, it is directly proportional to the area and the dielectric constant and is inversely proportional to the distance apart. Standard condensers are usually constructed with mica (or air for smaller values) as the dielectric.

If two condensers are joined in *parallel*, their joint capacitance is the *sum* of the individual capacitances, i.e. $C = C_1 + C_2$.

If they are joined in *series*, then the joint capacitance C is given by the relation

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \text{ or } C = \frac{C_1C_2}{C_1 + C_2}$$

Experiment 27. Measurement of Capacitance by Comparison with a Standard

When the condensers are of about the same value (say, 1 μF), the method adopted is to charge each separately to the same potential difference and to compare their charges by the kicks of a suitable galvanometer through which the

condensers are discharged. Provided the discharge takes place very quickly, the kick of the galvanometer is proportional to the charge. Also, the charge for the same voltage is proportional to the capacitance and, therefore, if C_1 and C_2 are the capacitances of the condensers giving kicks d_1 and d_2, we have

$$\frac{C_1}{C_2} = \frac{d_1}{d_2} \text{ or } C_1 = C_2 \times \frac{d_1}{d_2}$$

from which C_1 may be calculated if C_2 is known. The circuit is shown in Fig. 35. One terminal of the condenser C_1 is connected to the centre terminal of a double-throw switch S, which must have good insulation (porcelain or ebonite). The other terminals of S are connected to a 2-volt cell and the galvanometer as shown. Across the galvanometer terminals is a tapping key k to be used for the purpose of bringing the galvanometer quickly to rest after a throw by depressing it for a few seconds. k must be open for the main experiment.

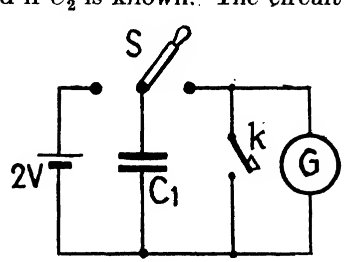

FIG. 35. MEASUREMENT OF CAPACITANCE BY COMPARISON

The condenser is charged for about 5 secs. by turning S over to the battery connexion. The zero of the galvanometer is observed and then S is turned over immediately to the right and the first throw of the galvanometer observed. d_1 is obtained as the mean of several such observations. Then C_1 is replaced by C_2 (whose capacitance is known) and the procedure repeated to obtain d_2. The value of C_1 is then calculated as shown above. If the throws are small, the battery should be increased to 6 or 10 volts until reasonably large throws are obtained.

If the condensers to be compared are such that one (say C_1) has ten times the capacitance of the other, a better plan is to use different voltages (of known values) for each, and to adjust the voltages so that the throws are approximately the same. If C_1 is charged to V_1 giving a throw d_1 while C_2, charged to V_2, gives d_2 (nearly equal to d_1), then

$$\frac{C_1 V_1}{C_2 V_2} = \frac{d_1}{d_2} \text{ or } C_1 = C_2 \times \frac{d_1}{d_2} \times \frac{V_2}{V_1}$$

In the case mentioned where $C_1 = 10C_2$, then C_1 might be charged to 1·5 volts and C_2 to 15 volts from a grid-bias battery, the actual voltages being measured by a voltmeter.

Experiment 28. Condensers in Parallel and in Series

The laws for condensers in parallel and in series given in the first part of this chapter may be confirmed by measurements made in a manner similar to that of the previous experiment.

The galvanometer throws when C_1 and C_2 are separately discharged after charging to the same voltage are known. C_1 and C_2 are then connected in parallel and used as one condenser again charged to the same voltage. It will be found that the galvanometer throw is now $d_1 + d_2$ within experimental error, thus confirming $C = C_1 + C_2$.

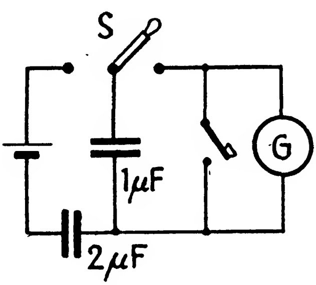

FIG. 36. CONDENSERS IN SERIES

Secondly, the condensers are joined in series and the mean value of the throw in this case is determined. Let it be d. Then the joint capacitance C is calculated from $C = C_2 \times \frac{d}{d_2}$ Also, C_1 and C_2 are known and therefore the value of C may also be calculated from $C = C_1C_2/(C_1 + C_2)$ and compared with that determined experimentally.

A further instructive experiment may be made with condensers in series if two condensers whose capacitances are unequal are used, suitable values being 1 μF and 2 μF. The circuit shown in Fig. 36 is set up. When S is closed to the left the condensers are charged in series by the battery (6 volts). On turning S to the right, the 1 μF condenser only is discharged through G. The throw is observed. After discharging the 2 μF condenser by connecting its terminals for a moment, the positions of the condensers are interchanged and the experiment repeated, thus measuring the charge on the 2 μF condenser. It will be found that the throws are the same in each case, so that condensers charged in series receive equal charges. Therefore, since $Q = CV$, the voltage across the 1 μF condenser is twice that across the 2 μF condenser.

Experiment 29. Discharge of a Condenser through a Resistance

When a resistance R is connected across the terminals of a charged condenser, a current flows through R, thus discharging the condenser. This current is equal to V/R where V is the instantaneous voltage between the condenser plates. Since V is continually falling as the discharge proceeds, the current also falls in value with time, which means that the charge Q diminishes more and more slowly with time in the manner shown in Fig. 37. The rate at which this loss of charge occurs depends on the capacitance C and the resistance

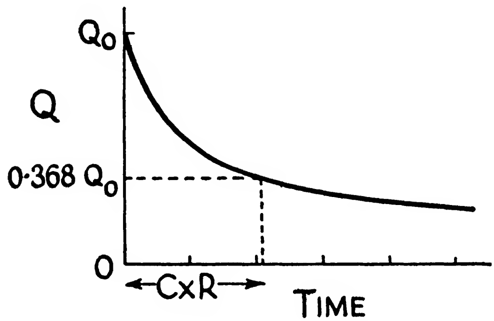

FIG. 37. DISCHARGE OF A CONDENSER THROUGH A RESISTANCE

R and it is measured in terms of the product $C \times R$ which is called the *time constant* of the circuit. It gives the time for the charge to fall to $\frac{1}{2\cdot718}$ (or 0·368) of its initial value.

If C is expressed in *farads* and R in *ohms*, then CR is in *seconds*. As an illustration of the values to be expected, let $C = 2\ \mu\text{F}$ and $R = 10\ \text{M}\Omega$, then the time constant $= 2 \times 10^{-6} \times 10 \times 10^6 = 20$ seconds.

(*a*) To Obtain the Discharge Curve of a Condenser and Measure the Time Constant

The circuit of Fig. 35 is set up using a 2 μF condenser with a resistance of about 5 megohms connected across its terminals. The battery voltage should be such that a galvanometer throw almost to the end of the scale is obtained when the condenser alone is used. First, the resistance is disconnected at the end joined to S, the condenser is charged and then

discharged through the galvanometer, the mean of several throws being taken. As explained earlier, the throw is proportional to Q. Secondly, R is reconnected, the condenser is charged and then S is opened for 2 seconds (measured on a stop-clock), at the end of which period the condenser is discharged through G, the throw giving a measure of the charge remaining on C. The observations should be made several times and the mean taken. This procedure is repeated for leak periods of 4, 6, 8 . . . seconds until the charge remaining is less than one quarter of the original charge.

A curve may now be drawn similar to that shown in Fig. 37, with galvanometer throws on the vertical axis and time of leak in seconds on the horizontal axis. On this graph the time taken for the throw to be reduced to 0·368 of the initial throw should be marked and read off. This is the time constant. Its value may be compared with the value of CR.

(b) To Measure the Insulation Resistance of a Condenser

Using a similar method, but with the $5\,M\,\Omega$ resistance removed, the condenser is charged and then allowed to leak on its own insulation. Owing to the much higher value of the leak resistance (provided the condenser is reasonably good), longer times of leak will be necessary, say 30 seconds, 1 minute, 2 minutes . . . . The periods of leak must be chosen so that the discharge curve does not come out too steep or too flat. As before, the time constant in seconds is found from the graph. Then knowing C, the value of R can be calculated. It will be several hundred megohms if the condenser is good.

In radio circuits very much smaller time constants than those measured here are used. In the case of a grid-detector circuit using a grid condenser of $0{\cdot}0003\,\mu F$ and a grid leak of $2\,M\,\Omega$, the time constant is $0{\cdot}0003 \times 10^{-6} \times 2 \times 10^{6} = 0{\cdot}0006$ second.

CHAPTER V

ALTERNATING CURRENT MEASUREMENTS AT LOW FREQUENCIES

ALTERNATING current theory is essential for the understanding of the working of almost every radio circuit. The experimental work described in this chapter is designed to illustrate the fundamental principles of A.C. theory, the measurements being made at low frequencies in order to avoid the difficulties which are peculiar to measurements at radio frequencies. R.M.S. values of current and voltage are used throughout.

Experiment 30. The Impedance, Inductive Reactance, and Resistance of a Coil

When an alternating current I passes through an inductive coil, the opposition to the current is expressed by the *impedance* Z, which is defined as the ratio of A.C. volts across the coil to I, the current through it, or $Z = V/I$. The impedance of any circuit to A.C. consists of two parts, the *resistance* R and the *reactance* X, and these are related to Z by the equation $Z^2 = R^2 + X^2$. In the case of a coil whose inductance is L, the reactance X_L is equal to ωL, or $2\pi f L$ where $f =$ the frequency. If V is expressed in volts and I in amperes, then Z, R, and X are in ohms.

In the above statement, R is the resistive component of the coil and may differ from the D.C. resistance. At low frequencies, however, and in the absence of an iron core, the difference is inappreciable.

A suitable coil for this experiment is one of 500 to 1000 turns, with a resistance of 10 to 30 Ω and an inductance of about 0·1 henry. It should be capable of carrying currents up to 1 amp.

(*a*) The resistance R of the coil is determined by D.C. It is placed in series with a moving-iron or thermo-ammeter (0–1) and a rheostat (50 Ω) set at maximum value to begin with, and connected to a battery of 12 volts.

Across the coil is connected a universal meter (Avometer or Taylormeter) set on a suitable D.C. voltage range. The current through the coil is adjusted to 0·4, 0·5, 0·6, 0·7 amp. in turn and the corresponding voltage measured. Then the

ratio V/I is worked out for each value, and the mean gives the resistance R.

(*b*) The impedance Z is determined by sending an alternating current through the coil and measuring the A.C. voltage across it. The circuit is shown in Fig. 38, T being a transformer on the 50 c/s A.C. mains, giving a supply at about 30 volts. A "Variac" transformer, in which this voltage

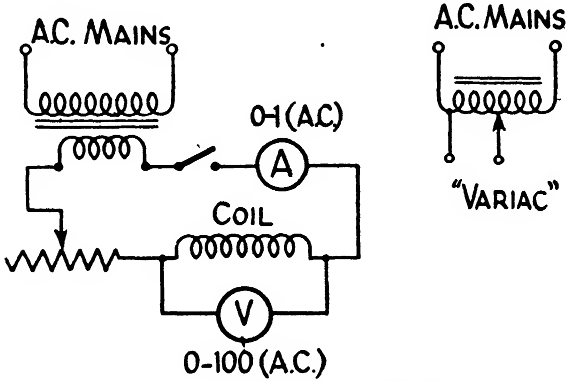

FIG. 38. TO MEASURE THE IMPEDANCE OF AN INDUCTIVE COIL

is continuously adjustable, may be used in place of a transformer of fixed ratio, if available.

The voltmeter is switched to the 100-volt A.C. range, and, starting with maximum resistance in the rheostat, the current is adjusted to 0·4, 0·5, 0·6, 0·7 amp. in succession. At each value of current the A.C. voltage across the coil is read. Working out V/I for each value, the mean gives the impedance Z.

(*c*) The reactance X_L and the inductance L may now be calculated from the measured values of Z and R. The reactance is given by $X_L = \sqrt{Z^2 - R^2}$ and the inductance by $L = X_L/2\pi \times 50$, since $f = 50$ c/s. L will be in henrys if X_L is in ohms.

Experiment 31. Variation of Impedance of an Inductive Coil with Frequency

As described above, the impedance Z of an inductive coil has two components, one resistive and the other reactive.

In the case of an air-cored coil carrying A.C. of low frequency, the resistance is practically constant, while the reactance increases with frequency, being equal to $2\pi fL$ and therefore proportional to the frequency. Thus Z, which is given by $Z^2 = R^2 + 4\pi^2f^2L^2$, increases with frequency because of this increase in the reactance.

In order to confirm this dependence on frequency, an

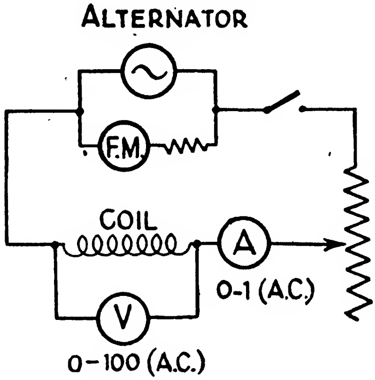

FIG. 39. TO INVESTIGATE VARIATION OF IMPEDANCE WITH FREQUENCY

alternator is required, the frequency of whose output can be varied (by altering the speed). Unless specially designed, such machines do not give a voltage which varies with time according to a pure sine curve, but one which contains harmonics, which are frequencies whose values are integral multiples of the fundamental. An alternator gives only the odd harmonics, i.e. those which are 3, 5 . . . times the fundamental. It is possible to design a filter circuit which will cut out these frequencies and leave only the fundamental, but this is hardly necessary in working with an inductive coil where it may be shown that the harmonic content of the total current is a small fraction generally less than 1 per cent. For the purpose of this experiment, an alternator giving frequencies from 60 to 120 c/s is suitable, the precise frequency for any particular measurement being given by a frequency meter connected through a resistance to the supply terminals as shown in Fig. 39, which also shows the general circuit.

The ammeter is a moving-iron or thermo-ammeter, while

the voltage across the coil is measured by a universal meter set on the 100-volt range. Measurements should be made at frequency intervals of about 10 c/s.

At each frequency, the rheostat is adjusted to give a constant current of, say, 0·6 amp. The. frequency meter reading and the voltmeter reading are taken. Then the impedance $Z = V/I$ is calculated at each frequency and Z^2 and f^2 are also found, using a table of squares.

Since $Z^2 = R^2 + 4\pi^2 f^2 L^2$, we should expect to obtain a straight line graph by plotting Z^2 against f^2, the line, however,

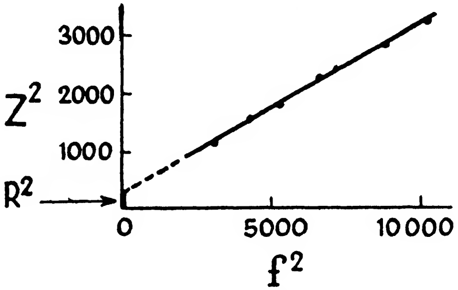

FIG. 40. VARIATION OF IMPEDANCE WITH FREQUENCY

not passing through the origin, but giving an intercept $Z^2 = R^2$, which is the value at $f = 0$. This graph is shown in Fig. 40.

Having drawn the best straight line through the points and produced it back to give R^2, the value of L may be found from the slope of the line, since this is equal to $4\pi^2L^2$. As an example of this calculation, the following figures are taken from the results of such an experiment—

At $f^2 = 10{,}000$, $Z^2 = 2960$
,, $f^2 = 0$, $Z^2 = 150$ ($= R^2$)

$$\text{Hence slope of the line} = \frac{2960 - 150}{10{,}000} = 0{\cdot}281$$

giving
$$4\pi^2L^2 = 0{\cdot}281$$
$$L^2 = \frac{0{\cdot}281}{40} = 0{\cdot}0070$$
$$\therefore L = 0{\cdot}084 \text{ henry}$$

It may be noted that R is about 12 Ω.

Experiment 32. Alternating Current through a Condenser

When an alternating voltage is applied to a condenser, the opposition to the current is purely reactive and thus the impedance is equal to the reactance. The reactance of a condenser of capacitance C is $X_C = 1/\omega C = 1/2\pi fC$ and, therefore, if I is the current when the voltage is V,

$$\therefore \quad \frac{V}{I} = \frac{1}{\omega C} \text{ or } I = V\omega C$$

Before commencing the experiment, which has as its objects the measurement of the reactance and capacitance of a

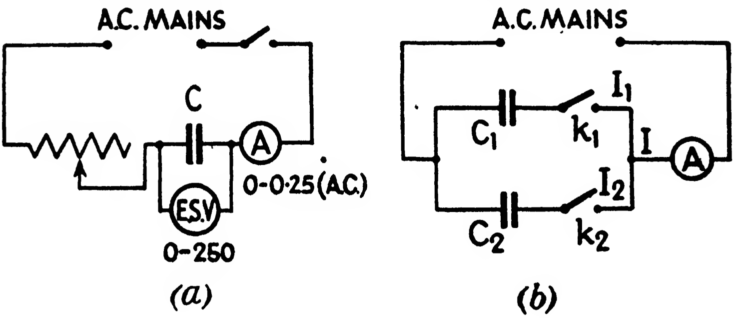

FIG. 41. (a) TO DETERMINE THE REACTANCE OF A CONDENSER
(b) CONDENSERS IN PARALLEL ON A.C. MAINS

condenser and the confirmation of the law for condensers in parallel, it is useful to calculate the impedance of a 1 μF condenser at a frequency of 50 c/s. This is

$$Z = X_C = \frac{1}{2 \times 3{\cdot}14 \times 50 \times 1 \times 10^{-6}} = \frac{10^6}{314} = 3180\,\Omega$$

Similarly, for a 2μF condenser at the same frequency, Z = about 1600 Ω. If, therefore, we wish to vary the current appreciably, rheostats having values of this order are required.

Also, in order to measure the voltage across a condenser, an electrostatic voltmeter is the proper instrument to use, as otherwise there will be a resistance in parallel which (as will be seen in a later experiment), will considerably alter the current.

(a) TO MEASURE THE REACTANCE OF A CONDENSER AT 50 c/s

The circuit is shown in Fig. 41 (a). The A.C. mains are connected in series with a rheostat of about 1000 Ω, a universal

instrument set on the range 0–250 mA (A.C.), and the 2 μF condenser under test. The electrostatic voltmeter (0–250 volts) is connected across C. Starting with the maximum rheostat resistance, the current is adjusted to 100, 120, and 140 mA in turn and at each value, the voltage across C is carefully measured. The value of V/I is worked out in each case and the mean gives Z (or X_C). Then C is calculated (in μF) from $X_C = 1/2\pi fC$.

(*b*) CONDENSERS IN PARALLEL ON THE A.C. MAINS

Using two condensers C_1 and C_2 whose capacitances are 1μF and 2μF respectively, the circuit shown in Fig. 41 (*b*) is set up with switches k_1 and k_2 in the condenser leads and a 0–250 mA A.C. ammeter in the main lead. When k_1 is closed and k_2 open, the current I_1 through C_1 is measured. When k_1 is opened and k_2 is closed, the current I_2 through C_2 is similarly measured. When both k_1 and k_2 are closed, the current I through the condensers in parallel is measured with the same voltage across them as when used separately. It will be seen that $I = I_1 + I_2$ and, therefore, the combined capacitance $C = C_1 + C_2$. Also, the currents I_1 and I_2 will be proportional to the values of C_1 and C_2, or, $\frac{I_1}{I_2} = \frac{C_1}{C_2}$, which should be checked from the measured values of the current and the known (or measurable) values of C_1 and C_2.

Experiment 33. Variation of Reactance of Condenser with Frequency

From the equation $X_C = 1/2\pi fC$, it is seen that the reactance of a condenser is inversely proportional to the frequency, which means that if, for example, the frequency is doubled, the reactance is halved. With a fixed condenser, it would be expected that $X_C \times f =$ a constant. In order to confirm this dependence on frequency, which is best done in the range 200 to 1000 c/s owing to the difficulty of obtaining alternators giving lower frequencies without harmonics, certain apparatus not hitherto described is necessary. The supply is provided by a standard valve oscillator whose output is practically free from harmonics over the range mentioned and may be adjusted to about 20 volts. Such oscillators are generally operated from the A.C. mains. It is also necessary to be able

to set the frequency at definite known values. Unless the frequency scale of the oscillator has been recently calibrated, it is preferable not to rely upon it, but to set the frequencies by reference to standard tuning forks in the manner to be described. This, of course, amounts to a calibration of the scale at the time of the experiment. In order to measure the voltage across the condenser, a valve voltmeter is used. This instrument will record alternating voltages up to high frequencies without putting any appreciable load on the circuit. It is unnecessary, at this stage, to understand how it works,

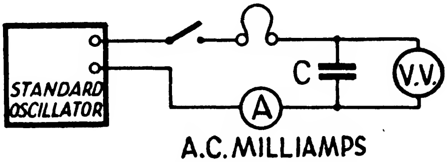

FIG. 42. MEASUREMENT OF X_C AT VARIOUS FREQUENCIES

provided the adjustments to be described are carried out. The valve voltmeter scale may be assumed to be correct.

The circuit is shown in Fig. 42, the ammeter being an Avometer set on the 0–12 mA A.C. range, and the condenser C being a mica condenser of 0·2 μF. In the circuit there is also a low-resistance telephone for the purpose of setting the frequency.

Before switching on the oscillator, the valve voltmeter must be adjusted. Connecting a battery of proper voltage for the valve, the switch is turned to "Battery" or "Set" position and a second control on the instrument is adjusted until the pointer stands at a fixed mark on the scale, generally indicated by a red line.

The switch is then turned to the range desired (25 volts) and the instrument is ready for use. Next the oscillator is switched on and its frequency set to approximately that of a standard tuning fork, say 256 c/s. The note heard in the telephone is allowed to beat with that of the fork, both notes being received by one ear at the same time, and the oscillator frequency is carefully adjusted until the rate of beating is less than 1 per second. Observations of current and voltage are then made and the value of $X_C = V/I$ is calculated.

Measurements of the same kind are carried out at other

standard frequencies, e.g. 384, 512, 768, 1024 c/s. Care should be taken to see that the current range of the Avometer is altered, if necessary, as the frequency is increased. At the conclusion of measurements, the oscillator should be switched off and the valve voltmeter switch returned to the "Off" position and the battery disconnected.

From the observations, X_C is calculated at each frequency. As the frequencies mentioned are in the ratio 2, 3, 4, 6, 8, X_C may be multiplied by these numbers instead of the actual frequencies, to show that $X_C \times f =$ constant.

Experiment 34. The Cathode-ray Oscillograph—Observation of Phase Difference

The cathode-ray oscillograph is an instrument extensively used in radio work, where its principal application is to investigate voltage waveforms of various types and under many different conditions. The principle of the cathode-ray tube is relatively simple. In a highly evacuated tube, a fine beam of electrons produced from a heated filament is focused on to a fluorescent screen at the end of the tube, giving a blue or green fluorescent spot at the centre of the screen. In its passage down the tube, the beam passes between two pairs of parallel plates, connected to terminals outside the tube. When a p.d. is applied between the plates of either pair, an electric field is set up which deflects the electron beam so that the spot moves on the screen. The two pairs of plates are arranged so that the deflexions produced by them are at right angles, the X plates producing a horizontal deflection and the Y plates a vertical deflection of the spot. These deflexions are proportional to the p.d.'s applied to the plates at any instant.

In a double-beam tube, the beam is divided into two and there are two pairs of Y plates (Y_1 and Y_2) which act independently on the two parts of the beam. Two fluorescent spots appear on the screen.

In addition to the tube, all oscillographs contain electrical circuits, switches, and controls. A description of the use of many of these will be found in a later experiment (No. 56) and only those necessary for the present observations of phase difference will be described here. The X and Y shift controls are used to move the spot or trace as a whole in the X and Y directions respectively. There are also controls for brilliance and focus.

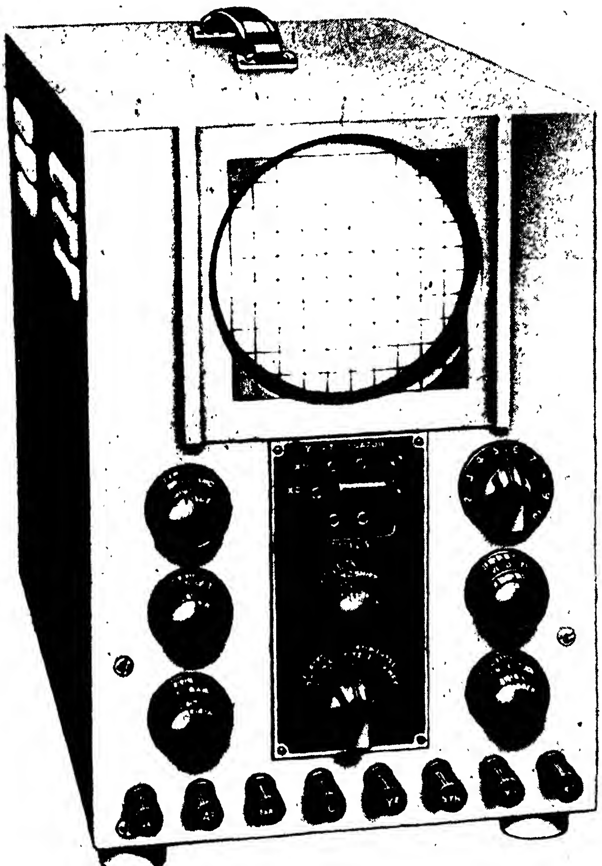

PLATE IV. DOUBLE BEAM CATHODE-RAY OSCILLOGRAPH (COSSOR)
(*By courtesy of the Manufacturers*)

One of the most important adjuncts is the time-base circuit. When this is brought into use, the spot moves across the screen in a horizontal line with a constant velocity from left to right. Coarse and fine frequency (or velocity) controls are used to adjust the speed of this motion. After having moved across the screen, the spot flies back in a very short interval of time and then retraces its path, giving the appearance of a continuous line on the screen. When the voltage to be examined has a periodic form, it is usually desirable to lock the trace so that it is stationary. This is accomplished by a synchronizing control, which should be applied only just sufficiently to secure the locking.

The oscillograph unit is supplied from the A.C. mains.

(*a*) Before proceeding to the question of phase difference, the following simple observations will illustrate the use of the instrument, which is shown in Plate IV.

(i) Observe the action of the brilliance and focus controls.

(ii) Operate the X and Y shift controls and thus, in a double-beam tube, distinguish between the Y_1 and the Y_2 beams.

(iii) Apply about 30 volts from an A.C. mains transformer between one of the Y terminals and E (the earth terminal). The R.M.S. voltage V may be measured by a suitable instrument. On the screen there will be seen a vertical line whose length represents the swing from positive peak to negative peak, i.e. it represents $2 \times \sqrt{2}V$ volts. By measuring the length of this line the sensitivity of the oscillograph in the Y direction may be calculated in mm./volt.

(iv) Keeping the A.C. voltage applied, turn on the time base and adjust it until an almost stationary trace is obtained. Then lock the trace by the synchronizing control. Examine also the adjustment of time-base speed to give 1, 2, 4, 6 . . . complete cycles on the screen.

(*b*) For observing phase relationships a double-beam tube is convenient and the following description implies the use of such a tube.

First, the transformer secondary giving about 30 volts is connected to two non-inductive resistances of 1000 Ω each in series. The centre point of the resistances is connected to E

and the outside terminals to Y_1 and Y_2, as shown in Fig. 43 (*a*). The time base is adjusted as in (iv) above and the two beams are brought together by the Y shift controls. It will be seen that the voltages across the resistances reach their maximum values at the same instant and are, therefore, in phase. The current in a non-inductive resistance is in phase with the voltage across it.

Secondly, one of the resistances is replaced by a 100 Ω rheostat and the other by an air-cored inductive coil of low

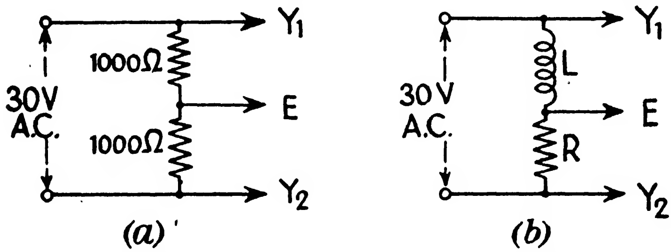

FIG. 43. (*a*) VOLTAGES IN PHASE WITH CURRENT; (*b*) TO SHOW PHASE DIFFERENCE BETWEEN CURRENT AND VOLTAGE IN AN INDUCTIVE COIL

resistance and high inductance (a coil of 1000 turns with resistance 30 Ω and inductance 0·3 H is suitable), the arrangement now being that of Fig. 43 (*b*). The traces are adjusted as before, when it will be observed that the voltage across R, which is in phase with the current in the circuit, lags behind the voltage across L by almost 90°.

Thirdly, the inductive coil is replaced by a 2 μF condenser and the 100 Ω resistance by one of 1000 to 1500 Ω. The Y_1 beam will give the voltage across the condenser, while the Y_2 beam will give the current through the condenser. Proceeding as before, it will be found that the current now leads the voltage by 90°.

Experiment 35. Phase Relation between Current and Voltage in an Inductive Coil

When an alternating current I passes through a coil whose inductance is L and whose resistance is R, the voltage across the coil is ZI, where Z is the impedance. This voltage has two components, RI in phase with I and ωLI, whose phase is 90° ahead of I, since in a pure inductance the current lags

by 90° on the voltage. These voltages are represented by vectors as shown in Fig. 44, where the length of the lines gives the magnitude of the voltages, and the angle which they make with the positive reference vector (which in this case is the vector for I) gives the phase angle by which the voltage leads the current. ZI is the vector sum of RI and ωLI. The angle ϕ is called the phase angle of the coil and is the angle by which the voltage across the coil leads the current through it.

Dividing each side of the voltage triangle by I, the smaller triangle in Fig. 44 is obtained, its shape being similar to that of the larger triangle and its sides being equal to Z, R, and ωL. It will be noticed that this triangle expresses the relation $Z^2 = R^2 + \omega^2L^2$, and also that $\tan \phi = \omega L/R$ and $\cos \phi = R/Z$. If, therefore, Z and ϕ are determined at a known frequency ($f = \omega/2\pi$), the other constants of the coil at that frequency can be calculated.

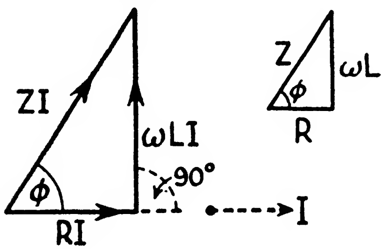

FIG. 44. VOLTAGE RELATIONS IN INDUCTIVE COIL

In order to measure Z and ϕ, the coil is placed in series with a non-inductive resistance R_1 and observations are taken of (i) the current, (ii) the voltage V_1 across R_1, (iii) the voltage V_2 across the coil, and (iv) the voltage V across R_1 and the coil. It will be seen that $V_1 + V_2$ is greater than V. This is accounted for by the fact that, whereas V_1 is in phase with I, V_2 leads I by the angle ϕ. V is the vector sum of V_1 and V_2 and a triangle may be drawn with sides equal to V_1, V_2, and V, as shown in Fig. 45 (*b*), from which ϕ may be obtained.

For the measurements, the coil, similar to that used in Experiment No. 30, is connected in series with a rheostat of about 90 Ω, and an A.C. ammeter 0–1 amp. to the secondary of a mains transformer giving about 30 volts. A voltmeter 0–100 volts A.C. is arranged so that it may be connected across R_1, across the coil, or across both R_1 and coil to measure V_1, V_2, and V, as shown in Fig. 45 (*a*).

The circuit should be adjusted so that V_1 and V_2 are approximately equal, while I = about 0·6 amp. Having taken the

necessary readings carefully, the voltage triangle ABC is drawn on a scale which should be such as to give a large triangle. AB is produced and then CD is drawn perpendicular to AB produced. Then the angle ϕ, which may be measured by a protractor, is the phase angle for the coil, and the triangle CBD is the triangle of voltages for the coil alone. The value of Z is given by V_2/I. It is then possible to calculate $R = Z \cos \phi$ and the reactance $X = \omega L = R \tan \phi$. Knowing the

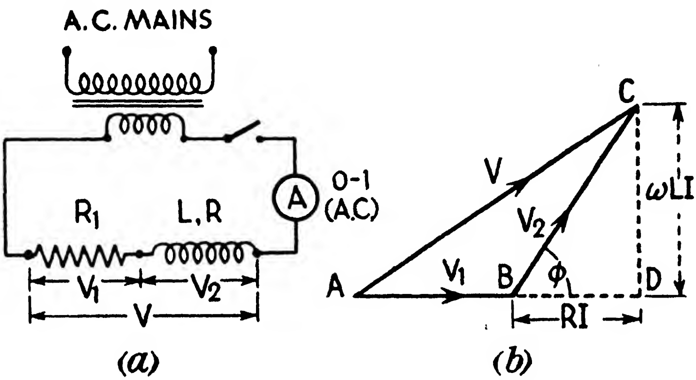

FIG. 45. (*a*) CIRCUIT TO OBTAIN TRIANGLE OF VOLTAGES; (*b*) TRIANGLE OF VOLTAGES

frequency (50 c/s), we have $L = X/2\pi f$. Alternatively, the values of R and X may be found by measuring the sides BD and CD, converting to volts, and dividing by I.

Experiment 36. Effect of an Iron Core on the Impedance and Effective Resistance of a Coil

When an iron core is introduced into a coil the impedance Z is very much increased. The effect of the iron is (i) to increase the reactance X by increasing L, and (ii) to increase the effective resistance R by reason of the extra work required in taking the iron through each cycle of magnetization. A suitable coil is a solenoid of about 1000 turns, similar to that used in Experiment 19, into which a core of iron wires may be introduced. The object of the experiment is to measure Z, L, and R for such a coil with the core inserted to various extents and to confirm the increases mentioned above. All

the measurements are carried out at the fixed frequency of the A.C. mains (50 c/s), the supply being about 30 volts from a mains transformer. The circuit is that of the preceding experiment, Fig. 45 (*a*), L being the iron-cored solenoid, but with R_1 variable. The procedure is also the same, except that the current I must be kept constant at, say, 0·2 amp. Starting with the core fully in, R_1 is adjusted to give this current and then V_1, V_2, and V are measured as before. Similar observations are made with the core one-half in and one-quarter in, care being taken to see that the current does not exceed the range of the ammeter as the core is withdrawn and that it is adjusted each time to 0·2 amp. by altering R_1.

Using graphical construction and calculating in each of the three cases exactly as in Experiment 35, the values of ϕ, Z, X, L, and R are found. The D.C. resistance of the coil should be measured by a universal meter for comparison with the A.C. resistance. On collecting and tabulating the results, it will be seen that there is an increase in all the quantities as more iron is inserted.

Experiment 37. Variation of Impedance, Inductance, and Effective Resistance of an Iron-cored Coil with Current

In the previous experiment, care was taken to keep the current constant, the reason being that the values of Z, L, and R depend on the current when the coil is iron-cored.

This dependence is to be examined in the present experiment. A circuit similar to that of Fig. 45 (*a*) is fitted up, using the iron-cored coil with core fully inserted and adding a rheostat by means of which the current may be adjusted. R_1 is retained at a suitable fixed value. The procedure and treatment of the measurements is exactly the same as in Experiment 35, the values of I, V_1, V_2, and V being measured at currents of 0·15, 0·2, and 0·25 amp. The last-named current is that at which, with the coil described, the iron is approaching saturation. The values of Z, L, and R are obtained as in the two previous experiments. As the current increases, the values of Z and L will be found to decrease. On the other hand, the effective resistance R increases.

The decrease in L is explained by the fall in the magnetic permeability of the iron. This reaches a maximum and then decreases as the magnetizing field is increased towards the saturation value. The work done in taking the iron through

its hysteresis cycle is, however, increased and this accounts for the greater part of the rise in R.

In the case of a low-frequency choke, which is an iron-cored inductance, similar effects would be found and if, in addition, it were carrying direct current, the values of Z, L, and R would be affected for the same reasons.

Experiment 38 (a). Capacitance and Resistance in Series

When an alternating current is passed through a condenser of capacitance C with a resistance R in series, the voltage RI

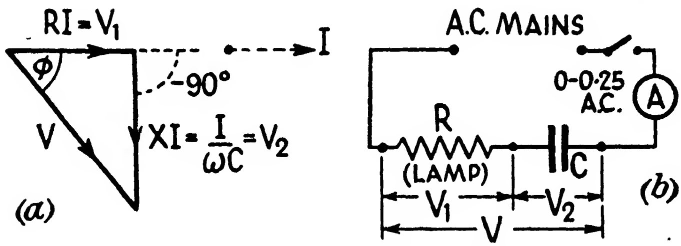

FIG. 46. (a) VOLTAGE VECTORS FOR C AND R IN SERIES (b) MEASUREMENTS WITH ALTERNATING CURRENT THROUGH C AND R IN SERIES

across R is in phase with the current, but the voltage XI across C (where X is the reactance) lags by 90° on the current. The voltage vector diagram is, therefore, that shown in Fig. 46 (a), V, which is the vector sum of RI and XI, being the overall voltage across C and R. Dividing each side of the triangle by I as in the case of an inductive coil, we see that the impedance Z has resistive and reactive components and is given by $Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + \frac{1}{\omega^2 C^2}}$, since $X = 1/\omega C$. The phase angle ϕ is negative, which means that the current leads the voltage. Its value, irrespective of sign, is given by $\tan \phi = 1/\omega CR$, and we have also $\cos \phi = R/Z$, so that if Z and ϕ are determined, the values of C and R may be calculated.

The circuit is shown in Fig. 46 (b). A 2 μF condenser is connected in series with a 230-volt 16-c.p. carbon lamp which forms the resistance, an A.C. ammeter of range 0–0·25 amp. and the A.C. mains (230 volts 50 c/s). The voltages across

the various components are measured by an electrostatic voltmeter whose leads are touched on to the points between which the p.d. is required. Switching on, and noting the current I, the voltage V_1 across the lamp is measured, then V_2 across the condenser and finally V, the voltage across the two.

It will be found that $V^2 = V_1^2 + V_2^2$, thus confirming that the voltage triangle is right-angled as in Fig. 46 (*a*). Then the triangle is drawn using a large scale and the angle ϕ is measured. Alternatively the angle may be calculated from

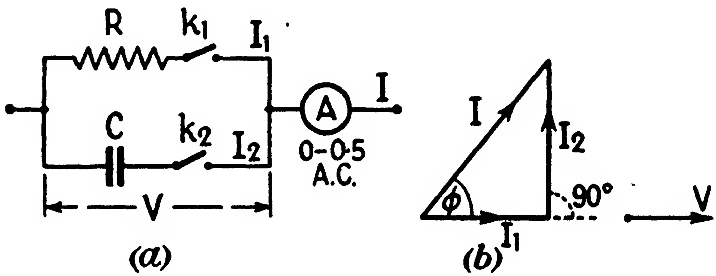

FIG. 47. (*a*) ALTERNATING CURRENT THROUGH C AND R IN PARALLEL: (*b*) CURRENT VECTORS FOR THIS CASE

$\tan \phi = V_2/V_1$. Z is found from V/I and then, using the relations given above, the values of R, X, and C are calculated. It should be noted that, in the series circuit, where the current is the same through each component, it is the voltage vectors which are plotted.

Experiment 38 (b). Capacitance and Resistance in Parallel

If a resistance R is connected across the terminals of a condenser of capacitance C and an alternating voltage V is maintained across them as shown in Fig. 47 (*a*), then the current I_1 through R is in phase with V, while the current I_2 through C is 90° ahead of V in phase. The total current I shown by the ammeter A is, therefore, not equal to $I_1 + I_2$, but to the vector sum of I_1 and I_2, as shown in Fig. 47 (*b*).

We should therefore expect $I^2 = I_1^2 + I_2^2$. This result may be confirmed experimentally and the value of ϕ for the parallel circuit found by connecting the circuit of Fig. 47 (*a*) to the A.C. mains, using for C and R the components of the previous

experiment. With the switch k_1 closed and with k_2 open, the value of I_1 is observed. Opening k_1 and closing k_2, the current I_2 is observed. Finally closing both keys, I is observed. It may then be shown by calculation that $I^2 = I_1^2 + I_2^2$ and the current vector diagram drawn on a large scale. The phase angle ϕ should be measured (or it may be calculated from $\tan \phi = I_2/I_1$) and the values of $Z = \frac{V}{I}$, $R = \frac{V}{I_1}$, and $X = \frac{V}{I_2}$ worked out, taking $V = 230$ volts. The relation between Z, R, and X for this parallel case may be found by considering the triangle obtained by dividing each side of the current vector triangle by V, which is the same for each. The sides of the resulting triangle would be $1/Z$, $1/R$, and $1/X$ so that $\frac{1}{Z^2} = \frac{1}{R^2} + \frac{1}{X^2}$. This relation can be checked by inserting the values of Z, R, and X already found.

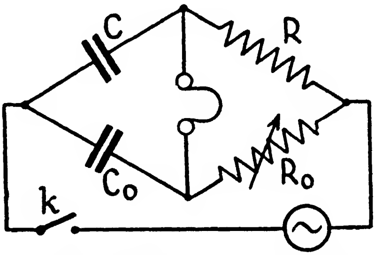

FIG. 48. CAPACITANCE A.C. BRIDGE

Experiment 39. Measurement of Capacitance by A.C. Bridge

When a standard mica condenser is available, the capacitance of a second condenser of about the same value may be measured with considerable accuracy by an alternating current bridge very similar to the Wheatstone bridge used with D.C. for measuring resistance. The circuit is shown in Fig. 48. The arms of the bridge consist of the condenser under test C, the standard condenser C_0, a fixed non-inductive resistance R and a variable non-inductive resistance, R_0, the resistances being taken from boxes.

The alternating current is supplied at an audio frequency of about 1000 c/s by a suitable oscillator whose output coil is connected to opposite junctions of the bridge. Across the other two junctions is connected a telephone, which replaces the galvanometer of the D.C. bridge and which is used to detect the balance with A.C. At balance, with perfect components, no alternating current will flow through the telephone and therefore no sound will be heard. In practice, the

adjustment is made until the intensity of the note heard in the phones is a minimum. When balance has been attained, $CR = C_0R_0$ giving $C = C_0R_0/R$.

Having connected the circuit, R is set at 1000 Ω and R_0 also at 1000Ω to begin with. The oscillator is switched on and the note in the phones is observed when the key k is closed. R_0 is then changed systematically until the note is a minimum. The accuracy of the setting should be tested by finding the change in R_0 which is required to give a just perceptible change in the intensity. This may be $\pm$ 2 Ω. Further measurements should be made with $R = 2000$ and 3000 Ω. C is then calculated for each balance and the mean taken. The following results taken from such an experiment, show the accuracy of the method, which, without refinement, should give the value of C to about 1 part in 1000.

C_0 (standard)	$= 0{\cdot}500_1$ μF	
R	1000	2000 Ω
R_0 for balance	951 ± 2	1903 ± 2 Ω
C	$0{\cdot}475_6$	$0{\cdot}475_8$ μF

If C has not a high insulation resistance, the minimum will be rather flat. In this case, the balance may be improved by connecting a variable resistance in series with C_0 and adjusting this resistance and R_0 alternately until balance is obtained.

Experiment 40. Capacitance and Inductance in Series

When a condenser and an inductive coil are in series and carry an alternating current, the voltage across the condenser lags behind the current by 90° while the voltage across the coil leads the current by an angle (the phase angle of the coil) whose value depends on the relation between the reactance and the resistance of the coil. The voltage V across condenser and coil together will be the vector sum of these two voltages, as shown in Fig. 49 (a), where V_C and V_L are the voltages across condenser and coil respectively. If the frequency is high enough to make the reactance of the coil much greater than its resistance, then V_L is almost in line with V_C and the resultant overall voltage is nearly equal to the difference between V_L and V_C.

If a non-inductive resistance R is included in series, then the voltage V_R across it is in phase with the current and the

vector diagram becomes that shown in Fig. 49 (*b*), where V' is the voltage across all three components.

The purpose of the experiment is to measure the various voltages in each case and to draw the vector diagrams.

An audio-frequency oscillator giving about 20 volts at 1000 c/s is used for the supply. It is connected through a switch to a 1 μF condenser, a wireless coil of 500 to 1000 turns, a resistance of about 200 Ω, and an A.C. ammeter of

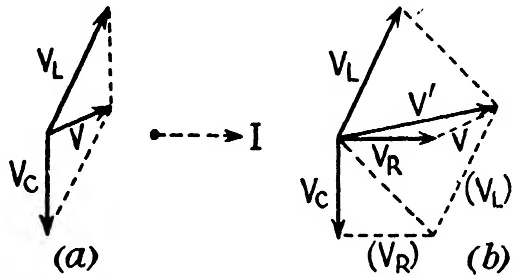

FIG. 49. VECTOR DIAGRAMS FOR: (*a*) CONDENSER AND INDUCTIVE COIL IN SERIES; (*b*) CONDENSER, INDUCTIVE COIL, AND RESISTANCE IN SERIES

range 0–250 mA. Throughout any set of measurements, the current is kept constant by adjustment of the volume control of the oscillator. The voltages across the components of the circuit are measured by a valve voltmeter with ranges 5, 25, 100 volts, adjusted as described in Experiment 33.

In the first set of measurements the voltages V_C (across C), V_L (across the coil), and V (across both) are measured. When doing this, the highest range of the valve voltmeter should be tried first and then the lower ranges as required. From the readings, the vector diagram of Fig. 49 (*a*) is drawn on a large scale. It may then be seen by what angle the phase difference between V_C and V_L is less than 180° and also what is the phase difference between the voltage V across the combination and the current I through it.

In a second set of measurements the voltages V_C, V_L, and V_R are measured as well as the voltage V' across the three components. If the current is the same as in the previous set of observations, V' is the vector sum of V_R and V, and since V_R is in phase with the current, the vector

diagram may be drawn to give V' and the value obtained graphically may be compared with the measured value.

Experiment 41. Measurement of the Inductance of a Low-frequency Choke by Turner's Method

Low-frequency chokes are iron-cored coils having large inductance (10 to 100 H in value). In order to measure such an inductance, the method to be described is very suitable if a decade dial variable condenser 0–1 μF is available. The

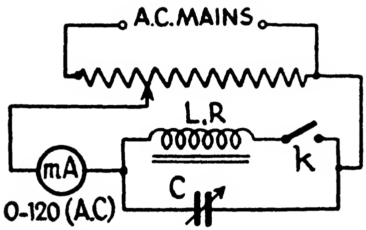

FIG. 50. TURNER'S METHOD FOR LARGE INDUCTANCES

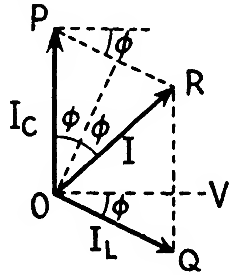

FIG. 51. CURRENT VECTORS IN TURNER'S METHOD

circuit is shown in Fig. 50. The choke (L, R) with a key in series is connected in parallel with a variable condenser C and the combination is connected to an A.C. supply at 50 c/s with an A.C. ammeter in the main circuit. For a certain value of C, the ammeter reading is the same whether the key is open or closed. When this is so, it may be proved, as shown below, that $2\omega^2LC = 1$ where $\omega = 2\pi \times$ frequency, L and C being expressed in henrys and farads, respectively.

The A.C. supply is obtained by means of a potential divider on the mains, the whole of a 1000 Ω rheostat being connected to the mains and tappings being taken from one end and from the slider to the circuit. Using an Avometer on the 120 mA A.C. range and with $C = 0{\cdot}5$ μF, the rheostat slider is set at about the centre and the current is switched on. The variable condenser is then adjusted until the reading of A is unchanged on opening or closing k.

The value of C is then noted and L is calculated from the relation given above.

By adjusting the potential divider, the experiment should

be repeated with a smaller and with a larger current. It will be found that the value of L depends on the current.

The remarkable point about Turner's method is that the resistance of the choke does not enter into the calculations.

The equation given may be proved by reference to Fig. 51, which shows the current vectors for the circuit.

The phase of the applied voltage is OV. The condenser current, I_C, represented by OP, is 90° ahead of the voltage. The inductance current I_L, represented by OQ, lags behind the voltage by the phase angle of the inductance ϕ. The main current I, represented by OR, is the vector sum of I_C and I_L. When C has been adjusted as described, $I = I_C$, so that the triangle OPR is isosceles. Bisecting the angle POR and drawing a line from P parallel to OV, it is obvious from simple geometry that all the marked angles are equal to ϕ. Then

$$\tfrac{1}{2}PR/OP = \sin\phi$$

or

$$\tfrac{1}{2}I_L = I_C \, . \sin\phi$$

But if Z = impedance of the coil, $I_L = V/Z$ and $\sin\phi = \omega L/Z$. Also $I_C = V\omega C$ and hence

$$\frac{1}{2} \cdot \frac{V}{Z} = V\omega C \times \frac{\omega L}{Z}$$

giving $2\omega^2 LC = 1$.

Experiment 42. Resonance Curve for Series Circuit.

In a circuit containing capacitance, inductance, and resistance in series (generally referred to as a series C–L–R circuit) the current which flows when an alternating voltage is applied depends on the impedance of the circuit, which is

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

and on the voltage V, being given by $I = V/Z$. The current lags behind or leads the voltage according as the reactance, which is $\left(\omega L - \dfrac{1}{\omega C}\right)$, is positive or negative. If the frequency or the values of L and C are adjusted so that this reactance is zero, we have the condition known as *resonance*, when the current will be a maximum, equal to V/R, and the impedance is purely resistive, being equal to R. In addition, the current

is then in phase with the applied voltage. The frequency f at which this occurs with fixed values of L and C is given by $\omega L = \frac{1}{\omega C}$, or $\omega^2 = 1/LC$, or $f = 1/2\pi\sqrt{LC}$. At frequencies near this resonant frequency the current in the circuit is less, falling off steeply if the value of R is small. A resonance or response curve for such a circuit shows the current as a function of frequency in the neighbourhood of resonance. The voltage across the condenser (or across the inductance)

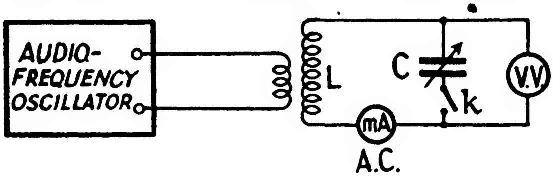

FIG. 52. TO DETERMINE THE RESONANCE CURVE OF A SERIES CIRCUIT

at resonance is much greater than the applied voltage V (which is that across R) and the voltage magnification is the ratio between these, i.e. V_L/V.

When, as in a tuned circuit, there is no added resistance and R is the resistance of the inductive coil, the voltage magnification is that of the coil and is denoted by Q. Since $V_L = \omega LI$ and $V = RI$, we have $Q = \omega L/R$.

In an experimental investigation of the resonance curve, instead of keeping the circuit fixed and altering the frequency of the supply, it is easier to keep the frequency fixed and to alter the resonant frequency of the circuit by de-tuning. This method, in fact, corresponds with that used in tuning a radio receiver.

To plot a resonance curve at about 10,000 c/s, the circuit shown in Fig. 52 is set up. The coil L is of about 700 turns with inductance 0·05 H, while the condenser C is variable between 0 and 1 μF. An A.C. milliammeter and a switch are included in the resonant circuit, across which the voltage is measured by a valve voltmeter. An audio-frequency oscillator is set to give a supply at 10,000 c/s, its output terminals being connected to a coupling coil of 200 to 500 turns by means of which a suitable voltage is injected into L by setting it near to L.

Having adjusted the valve voltmeter in the usual way, the first measurement is of the voltage V injected into the coil. This measurement is made with k open. Next, the voltmeter is switched to a higher range, k is closed, and C is adjusted until resonance is approached. This will be indicated by an increase in the milliammeter reading to a maximum. Having thus found the approximate condenser value for resonance, C is then set at a number of values on either side of resonance and at resonance, and at each point the values of V_L and I

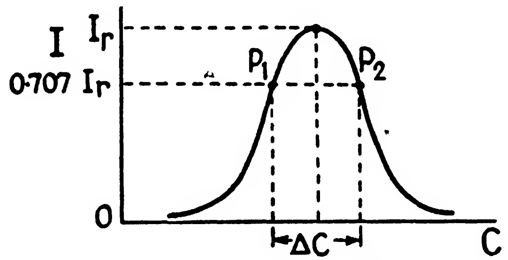

FIG. 53. RESPONSE CURVE SHOWING HALF-POWER POINTS

are observed. Smaller steps are needed when the curve rises or falls steeply.

The response curve is obtained by plotting I against C, and will be of the shape shown in Fig. 53. Reading off the value of C for resonance and knowing the frequency at which it occurs, the value of L may be calculated from the relation $f = 1/2\pi\sqrt{LC}$. Also, the voltage magnification, V_L/V at resonance, should be calculated from the voltage readings. Its value may be compared with the value of Q for the circuit found in the following way from what are called the half-power points on the response curve. These points are those for which the power is one-half the power in the circuit at resonance, i.e. the points at which the current is $1/\sqrt{2}$ or 0·707 of the current at resonance. They are shown at P_1 and P_2 in Fig. 53. If ΔC is the change in capacitance required to move from P_1 to P_2, the value of Q is given by $Q = 2C/\Delta C$ where C is the capacitance at resonance.

The voltage magnification of the circuit used will be less than the Q value of the coil because of the addition of the resistance of the milliammeter. The capacitance of the valve

voltmeter, which should strictly be added to C, is negligible in this experiment.

Experiment 43. The L.F. Transformer

In radio circuits, the low-frequency transformer is used for two principal purposes: (i) to supply, from the A.C. mains, suitable voltages for a power pack (see Experiment 90), and (ii) as a coupling in audio-frequency amplifiers (see Experiment 59). Two simple experiments on the transformer will serve to show the principles involved in its operation. The transformer in its simplest form consists of a continuous soft-iron core, built up from laminations which are electrically insulated from one another, and carrying two coils wound round the core, one being the primary of N_1 turns and the other the secondary of N_2 turns. These coils are insulated from each other and from the iron core. When an alternating current passes through the primary, the alternating magnetic flux in the iron is linked with the secondary, across which there is consequently an induced E.M.F. If the magnetic leakage is small, the ratio of secondary E.M.F. to primary E.M.F. is practically equal to N_2/N_1, which is called the turns ratio or transformation ratio T.

(*a*) A demonstration transformer suitable for testing the above relation may be made by winding a primary coil of 200 turns of No. 26 insulated copper wire and a secondary coil of 1000 turns of No. 30 insulated copper wire with a tapping at 400 turns, on the arms of a U-shaped laminated core with a straight laminated yoke which may be placed across the top of the U. Turns ratios of 2, 3, and 5 may thus be obtained. A supply at 4 volts obtained from a mains transformer is applied to the primary of this demonstration transformer. The secondary voltage is measured by an A.C. voltmeter of suitable range connected across the 400, 600, and 1000 turns in succession. The ratio of secondary to primary voltage is compared with the turns ratio in each case.

The effect of removing the yoke should also be investigated, first when it is taken off, and secondly when it stands on the U, but separated from it by a thin sheet of cardboard. These observations will show the necessity for a closed iron circuit.

(*b*) The second experiment is concerned with the efficiency of a mains transformer. It involves taking a current from

the secondary, with consequent increase in the primary current. When the secondary is open (i.e. no load), the primary current is small and consists of two components, one in phase with the applied voltage to supply the energy which is lost in the iron and the other lagging by 90° on the applied voltage due to the inductance and called the magnetizing current. The phase angle of the primary under these conditions may be found by using an oscillograph or by means of a wattmeter. It will be a constant for a particular transformer with fixed

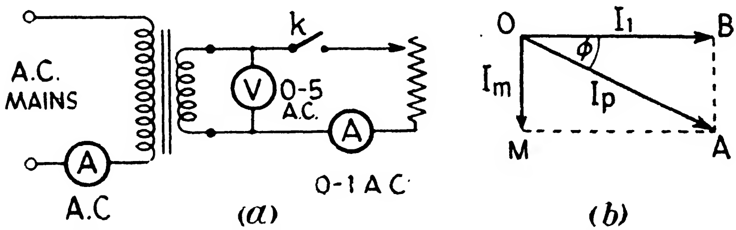

FIG. 54. (*a*) TO TEST THE EFFICIENCY OF A TRANSFORMER
(*b*) PRIMARY CURRENT VECTORS

primary voltage. We shall suppose its value to be 60°. Then the magnetizing current I_m will be 0·87 of the primary no-load current.

A mains transformer with a 4-volt 2-amp. secondary winding is used for the experiment. This secondary is connected through a switchto a 20 Ω rheostat and A.C. ammeter in series, as shown in Fig. 54 (*a*). The secondary voltage is also measured. In the primary circuit the current is measured by an Avometer on an appropriate A.C. range.

The following measurements are now made—

(i) With the switch *k* open, the no-load primary current is measured. I_m is then 0·87 of this value.

(ii) Turning the ammeter in the primary circuit to a higher range, the secondary circuit is completed and the secondary current adjusted to 1 amp. (at which value the efficiency is to be calculated). The primary current I_p and the secondary voltage V_2 are observed.

In order to calculate the efficiency, which is equal to $\dfrac{\text{secondary wattage}}{\text{primary wattage}}$ expressed as a percentage, it is necessary

to find the in-phase component of I_p. This may be done graphically or by calculation. Referring to Fig. 54 (*b*), *OM* represents the magnetizing current I_m, *OA* represents I_p, and *OB* represents the in-phase component I_1 which is required. Then $I_1 = I_p \cos \phi$, the value of ϕ being found from $\sin \phi = I_m/I_p$.

The primary wattage $= 230 \times I_1$ if the mains voltage is 230 volts. The secondary wattage is $V_2 \times 1$. Hence the efficiency can be calculated. Similar measurements may be taken

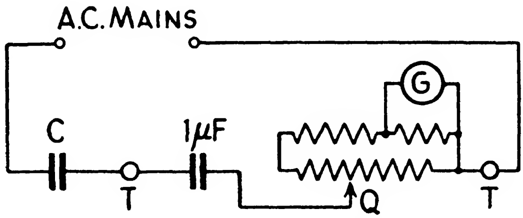

FIG. 55. MEASUREMENT OF CAPACITANCE BY AVOMETER

at other secondary load currents, such as 0·5 and 0·8 amp. Transformers are generally designed to be most efficient at full load, but the efficiency at smaller loads is not usually much lower.

Experiment 44. A.C. and other Tests on Condensers

The use of condensers in radio work is so extensive that a knowledge of the simple tests which may be made on them is indispensable.

(*a*) MEASUREMENT OF CAPACITANCE BY UNIVERSAL METER

Capacitance measurements with a universal meter are made in a way similar to resistance measurements, except that an A.C. supply is used. When the instrument switch is set at "Capacity," a 1 μF condenser is included internally and the deflexion gives the current when an A.C. supply is connected. If a test condenser of 1 μF is added in series, externally, the impedance is doubled and the deflexion falls to half-value, this point on the capacitance scale being marked 1 μF. The scale is thus calibrated to read directly in μF. Provided that the resistance of the meter circuit is relatively low, the calibration is independent of the supply frequency. Fig. 55

shows the arrangement with an Avometer, the terminals of the instrument when set with one switch at A.C. and the other at "Capacity" being shown at T, T.

Having connected the instrument to the A.C. mains, the knob Q is lifted and rotated until the pointer reads infinity on the capacitance scale. The mains are then switched off, the condenser C under test is inserted in series and the mains switched on again. C is then read from the scale. Several condensers should be measured and their nominal values compared with the measured values.

(b) Insulation Tests on Various Condensers

Comparative tests on the insulation resistance of mica, waxed-paper, and electrolytic condensers are made in the following way: The condenser is connected by a high-insulation switch to a D.C. supply of about 200 volts. Two H.T. batteries in series, each of nominal 120 volts, will serve. Across the condenser is connected an electrostatic voltmeter of range 0–250 volts. The connecting wires should be stiff so that they do not touch the bench. Commencing with a waxed-paper condenser of 2 μF, the condenser is charged and, opening the switch, the time required for the voltage to fall from, say, 200 to 100 volts, because of the leak through the insulation, is observed. Several readings should be made. Next the paper condenser is replaced by a 0·1 μF mica condenser and similar observations attempted. The difference between the two condensers will be obvious at once, the rate of leak being now so slow that an observation of the time for the voltage to fall from 200 to 190 volts will be sufficient. Thirdly, an 8 μF electrolytic condenser is used. In this case it is important to make sure that the positive pole of the battery is connected to the positive terminal of the condenser (generally the centre terminal, the metal case being the negative terminal). The slow rate of charging should be noticed. When the voltage has reached a satisfactory value, the leakage test is made immediately. Further experiments are then made when the maximum voltage has been applied for 1 minute and for 5 minutes. This will give time for some forming of the dielectric layer to take place and the rate of leak will be found to be less. The various results should be collected in a table.

(c) To Measure the Capacitance of an Electrolytic Condenser

A single electrolytic condenser must not be used on an alternating supply as this would result in the dielectric film being destroyed. It is, however, possible to measure the capacitance by alternating current provided a polarizing direct voltage is applied such as to prevent reversal of the polarity. The D.C. and A.C. voltages at the condenser terminals must satisfy two conditions—(i) the polarizing D.C. voltage must be greater than the A.C. peak voltage, (ii) the D.C. voltage + the A.C. peak voltage must be less than the maximum working voltage of the condenser. As the A.C. instruments will read R.M.S. values, it is necessary to make a calculation of the permissible values before commencing the experimental work. Suppose that the maximum working voltage of the condenser is 250 volts and let the maximum D.C. voltage of the 120-volts tapping of a H.T. battery be 108 volts. Then the maximum A.C. peak voltage would be $250 - 108 = 142$ volts. But this is greater than the available D.C. voltage. Hence the maximum A.C. peak voltage permissible = 108 volts, giving as the maximum R.M.S. voltage, $\frac{108}{\sqrt{2}} = \frac{108}{1{\cdot}41} = 76$ volts. For safety, it would be advisable not to exceed 65 volts (R.M.S.).

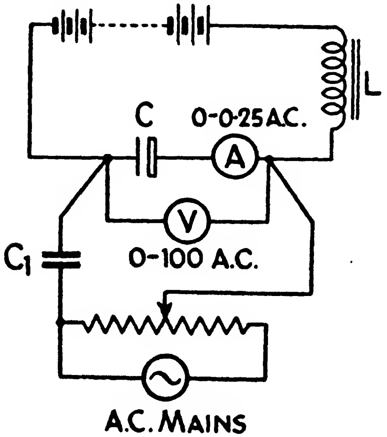

Fig. 56. To Measure the Capacitance of an Electrolytic Condenser

The circuit is shown in Fig. 56. The electrolytic condenser C with an A.C. ammeter (0–0·25 amp.) in series has both D.C. and A.C. voltages applied to it, the former from the 0–120 volt H.T. battery and the latter from a potential divider or a "Variac" transformer on the A.C. mains.

A low-frequency choke L must be included in the H.T. battery lead to prevent A.C. from passing through the battery and, similarly, a condenser C_1 of suitably high value (6 μF) must be inserted in the A.C. lead to prevent the H.T. battery from being shorted through the potential divider. The A.C. voltage tapped from the potential divider is thus applied to C and C_1 in series, but only that portion across C is measured by the A.C. voltmeter V, which is an Avometer set on the 100-volt A.C. range. This instrument will measure an A.C. voltage superimposed on a D.C. voltage because it has an internal transformer as well as a rectifier unit. Before switching on, it should be confirmed that the positive battery terminal is connected to the positive terminal of C and that the potential divider is set to give a very small A.C. voltage to begin with. This voltage is then set at 20, 30 . . . 60 volts in succession and the values of current I and voltage V across C are measured. The reactance $X_C = V/I$ is calculated for each pair of readings and finally C is calculated from $X_C = 1/2\pi fC$, the frequency of the mains being 50 c/s.

The value of C may be found to differ considerably from its nominal value.

CHAPTER VI

THE CHARACTERISTICS OF VALVES AND METAL RECTIFIERS

THE characteristic of any component of an electrical circuit is a curve showing the relation between the current I and the voltage V applied to the component, which produces it, the conditions under which the relation is expressed being specified.

Only if Ohm's Law applies to the component is the characteristic a straight line. In all the cases now to be considered the characteristics are curved and unsymmetrical, this being typical of all non-linear devices, as they are therefore called.

In this chapter, unless expressly stated to be otherwise, all the currents and voltages are direct currents and voltages.

Experiment 45. The Characteristic of a Metal Rectifier

All rectifiers have a much greater conductance for current passing in one direction than for current in the reverse direction. Two kinds of metal rectifier are in general use, copper-copper oxide and iron-selenium. In the first type, which consists of copper discs coated on one side with copper oxide and connected in series, the good conducting direction is from the oxide to the copper. In the second type, consisting of nickel-plated iron discs coated on one side with selenium, the conducting direction is from iron to selenium. In the diagrams, the rectifier is shown by an arrow head standing on a plate, the direction in which the arrow head points being the "forward" or good conducting direction.

The experiment consists in determining the relation between the current and voltage for the two directions, using a single element. The current in the forward direction should not generally exceed 150 mA/cm.^{2}, this corresponding to a voltage of about 1 volt with the copper oxide type and about 1·3 volts with the selenium type. In the reverse direction, the applied voltage should not exceed 12 to 15 volts, the current then being about 1 mA/cm.^{2} for each type.

Measurements in the forward direction are made by the circuit shown in Fig. 57 (*a*). A 2-volt cell is connected to a potential divider from which voltages between 0 and 1 volt

are applied to the rectifier element, the current being measured by a 0–1 ammeter.

Corresponding readings of I and V are obtained, care being taken not to exceed a current of 1 amp. For the reverse

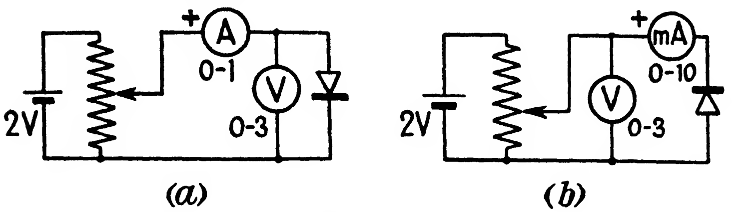

FIG. 57. CIRCUITS FOR METAL RECTIFIER CHARACTERISTICS (a) FORWARD DIRECTION; (b) REVERSE DIRECTION

direction, the circuit of Fig. 57 (b) is used, the ammeter being replaced by a 0–10 mA instrument and the voltmeter being so placed in the circuit that the current through it is not recorded by the milliammeter. Measurements of I when $V = 0$, 0·5, 1, and 2 volts are taken. From the reading of

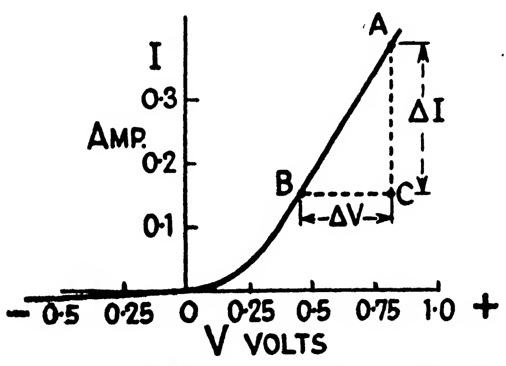

FIG. 58. CHARACTERISTIC OF A METAL RECTIFIER

I at 1 volt the resistance of the rectifier for the reverse direction should be calculated.

The characteristic is then plotted from the two sets of readings. It will be of the form shown in Fig. 58, and consists of a line very close to the axis for negative values of V, a curved part from $V = 0$ to about 0·3 volt and a practically

straight portion for higher values of V. Using this straight part, the forward resistance may be deduced from the slope of the line.

If a change ΔV in voltage produces a change ΔI in current, then $R = \Delta V/\Delta I$, these increments being found by drawing the triangle ABC on the straight part and measuring BC and CA in terms of their respective scales.

If a single element is not available, measurements may be

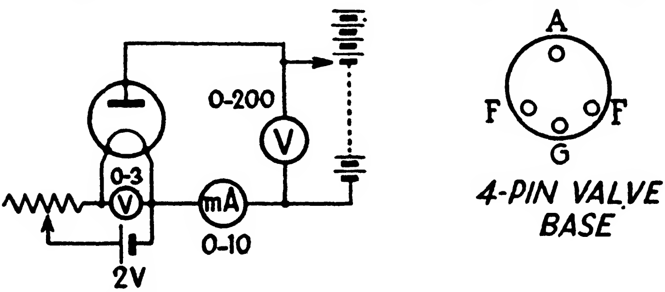

FIG. 59. CIRCUIT DIAGRAM FOR DIODE CHARACTERISTICS

made on a unit containing several elements, provided care is taken to see that the voltage per element does not exceed that stated and that the elements are all in series in the same direction. A unit is sometimes arranged with a centre terminal, the elements then being arranged so that their forward directions are from centre to each end.

Experiment 46. The Characteristic of a Diode

A diode is a thermionic valve with two electrodes—the filament or cathode and the plate or anode. When the filament is heated by a current, it emits electrons which are attracted to the anode when this electrode is positive with respect to the filament.

The electric current through the valve, according to convention, flows from anode to cathode. This anode current I_a depends, in a given valve, on the anode voltage V_a with respect to the filament and on the temperature of the filament. Thus an I_a–V_a characteristic can be drawn for each filament temperature.

The circuit for determining such characteristics is shown in Fig. 59, which also shows the 4-pin valve base. The valve

may be an Osram H.L.2 or similar type with anode and grid connected together to form the anode of the diode. Its normal filament voltage is 2 volts, the filament being supplied by a 2-volt accumulator with a rheostat of about $10\,\Omega$ in series. If desired, the voltage at the filament terminals may be measured by a voltmeter connected across them.

The anode voltage is obtained from a 0–120-volts H.T. battery and is applied between anode and the negative ter-

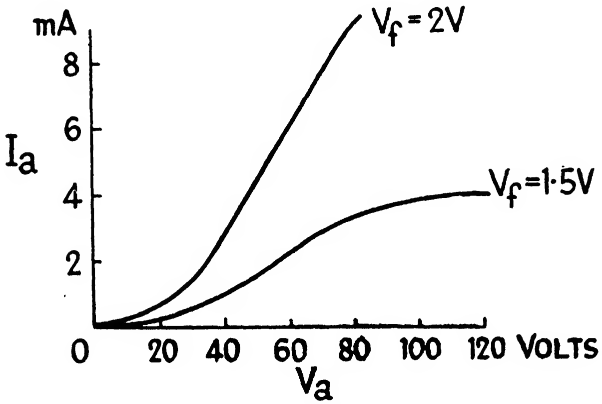

FIG. 60. I_a–V_a CHARACTERISTICS OF A DIODE

minal of the filament. V_a is measured by a voltmeter 0–100 or 0–200 volts across that part of the battery which is being used. The anode current I_a is measured by a milliammeter 0–10 mA, in the anode circuit, preferably on the low potential side.

With 2 volts on the filament, the anode current in mA is observed as V_a is increased in the steps provided by the tappings on the H.T. battery from 0 upwards. The anode current should not be allowed to exceed 10 mA. No reliance should be placed on the nominal voltages of the various battery tapping points. Although when $V_a = 0$, the milliammeter will show no appreciable reading, there is nevertheless a very small current which could be detected by a much more sensitive instrument.

A similar set of readings is then obtained with a lower filament temperature, say that corresponding to 1·5 volts on

the filament. Although the valve is not generally used under these conditions, the characteristic obtained will show the approach to saturation which occurs as V_a is increased.

On plotting the characteristics, curves similar to those shown in Fig. 60 will be obtained.

The upper curve (for 2 volts on filament) starts very near 0, bends upwards, and then becomes practically straight over a considerable range. Taking two points on this straight part, the differential or "slope" resistance, $R_a = \Delta V_a / \Delta I_a$ may be calculated as in the case of the metal rectifier. It must not be forgotten that ΔI_a must be expressed in amperes. The lower curve (for 1·5 volts or less on the filament) has a much shorter straight portion and proceeds to saturation.

Experiment 47. The Mutual Characteristics of a Triode

The triode is a valve with three electrodes, viz. anode, grid, and filament (or cathode), the grid being fixed between anode and cathode. There are thus several different types of characteristic, each showing the relation between a current and a voltage when other factors are fixed. These various characteristics will be the subjects of several experiments, in view of the importance of this particular valve. In all the experiments, the filament voltage is at the normal rating for the valve.

A mutual characteristic shows the relation between anode current I_a and grid voltage V_g, when the anode voltage V_a is fixed, the voltages being measured from the cathode (or negative end of the filament) to the electrode concerned. Special attention should be given to that part of the characteristic in the region of negative values of V_g, as this is the portion over which small triodes are normally operated. Positive values of V_g should never exceed 1 or 2 volts and should not be applied for longer than is necessary to read the anode current, as otherwise the filament will be permanently damaged.

The circuit is shown in Fig. 61, an Osram H.L.2 valve being used. The filament is connected to a 2-volt cell. In the anode circuit are a H.T. battery with a voltmeter (0–200) across the battery leads to measure V_a and a milliammeter (0–10 mA) to measure I_a. The grid voltage is provided from a potential divider across a 6-volt battery of accumulators with positive terminal connected to negative filament terminal

in the first set of measurements. A voltmeter (0–10) is used to record V_g.

Owing to the ease with which valves are damaged by wrong battery connexions, the circuit wiring should be carefully checked before any batteries are connected. This rule holds for all valve circuits.

Setting the slider of the potential divider so that the maximum grid bias of -6 volts is applied to the grid, the value of V_a is set at 60 volts (nominal) and the anode current

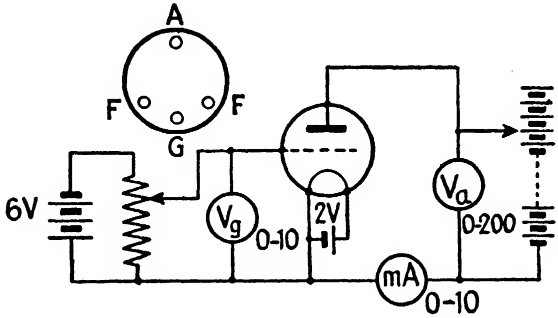

FIG. 61. CIRCUIT FOR CHARACTERISTICS OF A TRIODE

observed. Then, keeping V_a fixed, the grid voltage is varied in steps of 0·5 volt up to 0 and, at each value, the anode current is observed. This procedure is repeated for a number of different fixed values of V_a, say 48, 72, 90, 110, and 120 volts, these being nominal values of which the true values are read on the voltmeter. Next, after switching off, the 6-volt grid battery is replaced by a 2-volt cell connected so that a positive bias may be applied to the grid. Readings are then made as before, with $V_g = +0·5$ and $+1·0$ volt, at such of the former values of V_a as will give an anode current not greater than 10 mA.

A grid bias dry battery may be used to provide V_g in place of the potential divider and 6-volt accumulator. In this case, the steps of grid voltage available are greater, being 1·5 volts each, and it is necessary to take care that the H.T. connexion is broken before changing V_g to another value. Also, in making $V_g = 0$, the grid must be connected directly to the negative terminal of the filament and not left disconnected. The potential divider should not be used with a

dry battery as the current taken by it would soon run the battery down.

Having taken and tabulated the readings, the mutual characteristics, one for each value of V_a, are drawn by plotting I_a against V_g. The curves will be similar to those shown in Fig. 62 (*a*). It will be seen that, after the initial curvature,

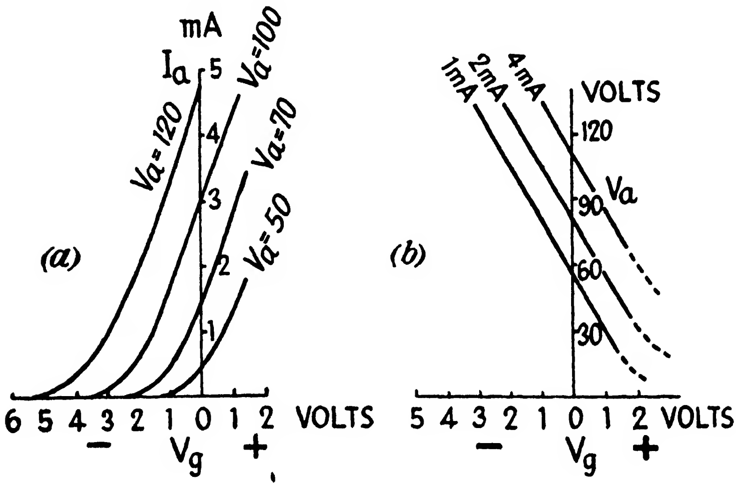

FIG. 62. (*a*) MUTUAL CHARACTERISTICS OF A TRIODE
(*b*) RELATION BETWEEN V_a AND V_g

the characteristics are practically straight and parallel. From the straight portion, the value of the *mutual conductance* g which equals $\Delta I_a/\Delta V_g$ when V_a is fixed, is calculated, ΔI_a being the change in anode current due to a change ΔV_g in grid voltage. g is usually expressed in mA/volt.

From the mutual characteristics, a second set of curves which show an important property of a triode may be obtained. Drawing a horizontal line across the mutual characteristics at $I_a = 2$ mA, the corresponding values of V_g and V_a to give this anode current are read off and plotted against each other to give a line for $I_a = 2$ mA as shown in Fig. 62 (*b*). Similar lines are obtained for $I_a = 1, 3, 4 \ldots$ mA, and it will be seen that these V_a–V_g lines for various constant currents are straight and parallel over the greater part of their length. This means that if the anode voltage is increased

by ΔV_a, then the decrease in grid voltage necessary to keep the anode current constant is proportional to ΔV_a. It follows that the ratio of anode voltage change ΔV_a to grid voltage change ΔV_g, required to produce the same change in anode current, is a constant. This constant is called the *amplification factor* of the valve and is denoted by μ. Its value may be found from the slope of the V_a–V_g lines, being equal to $\Delta V_a/\Delta V_g$ along a constant current line.

Experiment 48. The Anode Characteristics of a Triode

These characteristics show the relation between the anode current I_a and the anode voltage V_a for fixed values of grid voltage V_g. Although they may be obtained from the mutual characteristics, it is preferable to determine them in a separate experiment. The circuit is the same as in Fig. 61, except the arrangements for providing the grid voltage, which may now be obtained from a grid bias dry battery simply. First, with $V_g = 0$, i.e. with grid connected to the negative filament terminal, the values of I_a are observed when V_a has nominal values 12, 24, 36, 48, 60 . . . 120 volts. The actual values of V_a must be measured. In order to obtain the smaller values from a H.T. battery on which these tappings are not marked, the negative H.T. lead is placed in the 48- or 60-volts socket and the positive lead taken to a higher voltage socket, e.g. using the 48 and 72 sockets will give 24 volts (nominal). Other sets of readings are taken when V_g is fixed at $-1{\cdot}5$ and -3 volts and a few readings for such values of V_a as will keep the anode current below 10 mA may be taken with $V_g = +1{\cdot}5$ volts. As before, the H.T. battery should be disconnected when a change is made in V_g.

From the readings, the anode characteristics are plotted with I_a as ordinate and V_a as abscissa, their general form being shown in Fig. 63. After the initial curvature, they consist of practically straight parallel lines. On the straight part of one of them a triangle XYZ is drawn with XZ parallel to the axis of I_a and YZ parallel to the axis of V_a. Measuring YZ in volts and XZ in mA and converting to amperes, the differential or "slope" resistance in ohms is found from $R_a = \dfrac{\Delta V_a}{\Delta I_a} = \dfrac{YZ}{XZ}$. This is sometimes called the A.C. (anode characteristic) resistance of the valve.

If the experiment has been made with the same valve as that used for the mutual characteristics, the relation $\mu = g \times R_a$ can be tested. If not, then g may be found by noting on the anode characteristics the change in I_a due to changing V_g by 3 volts (from $-1{\cdot}5$ to $+1{\cdot}5$ volts) at a constant value of V_a, say 60 volts, and working out

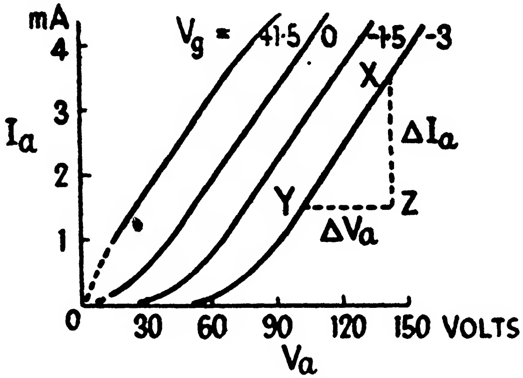

FIG. 63. ANODE CHARACTERISTICS OF A TRIODE

$g = \Delta I_a / \Delta V_g$. The relation $\mu = g \times R_a$ may then be used to calculate μ.

It is usually of interest to compare the measured values of g, R_a, and μ with those given in the makers' catalogue.

Experiment 49. The Dynamic Characteristic of a Triode

The characteristics obtained in the last two experiments are called static characteristics. When a load, such as a resistance, is included in the anode circuit, as in an amplifier stage, the I_a–V_g characteristic of the valve with load is called the dynamic characteristic and is different from the static characteristic, as will be shown in this experiment.

Considering the circuit of Fig. 64, when the anode load resistance R is included, there is a drop of volts across it equal to $R \times I_a$ and therefore, with a constant H.T. voltage, the anode voltage is less by this amount, and decreases as I_a increases, i.e. as the grid voltage is increased.

In the circuit shown, the valve is an Osram H.L.2 and the anode load is 30,000 Ω, which may be shorted by a switch.

The grid bias is provided by a potential divider with its fixed end terminals connected to a 6-volt accumulator and with its slider connected to the grid, V_g being measured by the 0–10 voltmeter as shown.

A static mutual characteristic for $V_a = 100$ volts is first determined. Fixing V_a at this value, the resistance is shorted

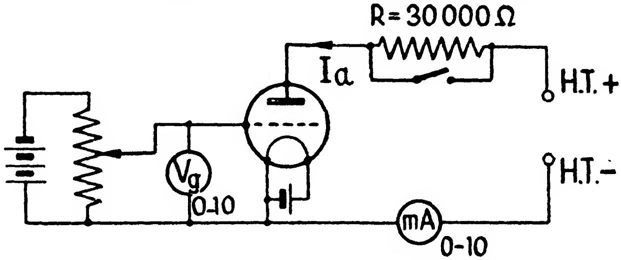

FIG. 64. CIRCUIT FOR DYNAMIC CHARACTERISTIC OF A TRIODE

by closing the switch and then readings of anode current for $V_g = 0, -1, -2, \ldots -6$ volts are taken. From these readings the static characteristic shown in Fig. 65 is drawn. When the valve with R included is used as an amplifying stage, the swing of voltage on the grid will take place about a point P, called the operating point and chosen generally so that the grid never becomes positive. Suppose the operating point is at $V_g = -2$ volts. Then the corresponding point on the characteristic is Q, and, in order to investigate the action of the amplifier, the dynamic characteristic through Q is required. At this point, with $R = 30{,}000\ \Omega$, the anode voltage is to be 100 volts. The H.T. battery voltage must therefore be increased to a value V given by $V = 100 + 30{,}000 \times I_a$, where I_a is the anode current at the point Q.

Opening the switch, so that R is included, the H.T. voltage is adjusted to this calculated value (by the addition of a portion of a second battery) and the readings for the dynamic characteristic may now be taken. V_g is set, as before, at $0, -1, -2, \ldots -6$ volts in turn and the anode current read. The dynamic characteristic SQT is then drawn.

It will be seen at once that the effective mutual conductance $g = \Delta I_a / \Delta V_g$ is smaller than in the static case. Its value should be calculated. The larger R, the smaller will be this effective mutual conductance.

A further experiment may then be carried out to show the relative phases of grid voltage, anode voltage, and anode current when the grid voltage is taken through a cycle of changes. If the slider of the potential divider is moved to and fro to give in turn the following values of V_g: -2, $-0{\cdot}6$, 0, $-0{\cdot}6$, -2, $-3{\cdot}4$, -4, $-3{\cdot}4$, -2 volts, these

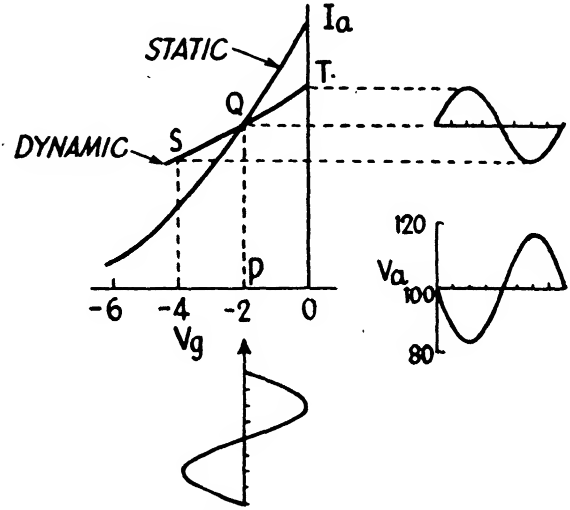

FIG. 65. DYNAMIC AND STATIC CHARACTERISTICS OF A TRIODE WITH RESISTIVE LOAD

correspond to the voltages on the grid when a cycle of sine waveform (shown below the axis in Fig. 65) is divided into 8 equal parts.

Setting V_g at these values, the anode current is measured at each and thus the cycle of anode current shown on the right may be plotted. The anode voltage at each point may be calculated from the known values of H.T. voltage, the anode current and R. These, being plotted on a similar base, will give the cycle of anode voltage as shown. The curves obtained confirm two very important results which apply when the anode load is a resistance: (i) I_a and the voltage across R are in phase with V_g, (ii) V_a and V_g are in opposite phase.

Experiment 50. The Grid Characteristics of a Triode

A grid characteristic shows the relation between the grid current I_g and the grid voltage V_g for a fixed value of anode voltage V_a. In order to obtain a grid current, the grid voltage will have to be positive, say up to 1 volt. Although the grid current is small, being measured in micro-amperes, its effect on the input circuit to the grid of a valve used as a detector or oscillator is a very important consideration.

In this experiment, two grid characteristics are determined,

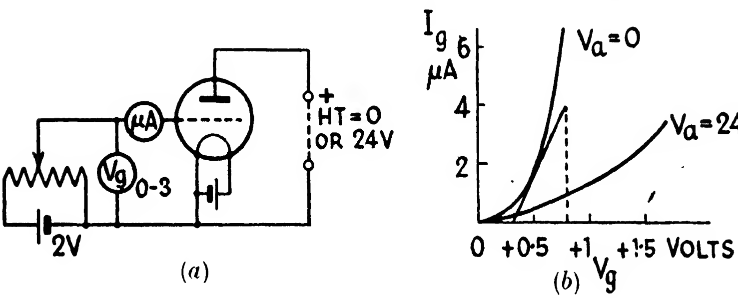

FIG. 66. GRID CHARACTERISTICS OF A TRIODE

one with $V_a = 0$ and the other with $V_a = 24$ volts, thus showing the effect on I_g when the valve takes anode current.

It will be necessary to use a suitable microammeter to measure I_g. This may be a moving-coil galvanometer for which the current per division deflexion (say 4μA/division) is known, or an Avometer Model 7 on its smallest current range which is 2 mA per 100 divisions, or 20 μA/division. The circuit is shown in Fig. 66 (*a*), the grid voltage being provided by a potential divider of 24 Ω connected to a 2-volt accumulator, and measured by the 0–3 voltmeter as shown. A suitable valve is a Tungsram S.P.220, taking 2 volts on the filament. Any similar small power triode would be satisfactory.

For the measurements at $V_a = 0$, the anode and negative filament terminal are connected and observations of I_g are made with V_g at values between 0 and 1 volt, increasing by steps of 0·1 volt. The grid current reading must be taken very carefully.

Secondly, V_a is made equal to 24 volts by the introduction of a H.T. battery and a further series of readings of I_g made

at the same grid voltages. The characteristics may now be plotted and will be of the form shown in Fig. 66 (*b*).

It will be noticed that the characteristics are curved in the region near the origin, thus making grid detection possible, and also that for a given grid voltage, the grid current is less when anode current flows. Not only is the current less, but the slope of the characteristic is smaller, indicating a larger differential resistance in the grid circuit. The values of this resistance ($= \Delta V_g/\Delta I_g$) at $V_g = 0{\cdot}5$ volt should be calculated by drawing a tangent to each curve at the appropriate points. One such tangent is shown in the diagram. When a tuned circuit is connected to the grid, and grid current flows, this resistance is in parallel with the tuned circuit and causes damping, with consequent reduction in the effective magnification Q of the circuit.

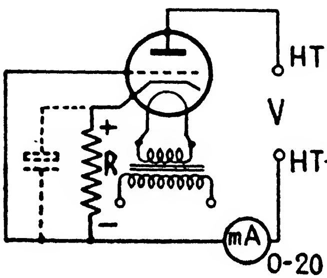

FIG. 67. CIRCUIT FOR INVESTIGATING CATHODE BIAS RESISTANCE

Experiment 51. Cathode Bias Resistance

It is often desired to have a grid-bias voltage which is not fixed, but which adjusts itself to the working conditions of a valve. A self-adjusting negative bias of this kind can be obtained very easily with an indirectly-heated valve by connecting the grid to the earth line and placing a resistance R between cathode and earth, as shown in Fig. 67. The total anode current I_a passes through R so that the cathode is positive with respect to the grid, i.e. the grid is negative with respect to the cathode, the negative bias voltage being then equal to $R \times I_a$. Its value therefore depends on I_a and increases as I_a increases. The bias is required to be steady and, therefore, if the anode current has an alternating component as in an amplifying stage where an alternating voltage is applied to the grid, a 16 μF electrolytic condenser is connected in parallel with R to by-pass the low-frequency component. In the figure, this condenser is shown by dotted lines as it is not required for the experiment.

The advantages of biasing by a cathode resistor are: (i) The

bias is self-adjusting to a large extent; if I_a is larger than normal, the negative bias will be greater, thus tending to reduce I_a. (ii) If the H.T. voltage varies, compensating changes are produced by a change in the grid bias.

A valve suitable for the experiment is an Osram M.L.4. It has a 5-pin base, the centre pin being connected to the cathode, while the usual filament pins are connected to the heater. This heater is supplied from the 4-volt winding of an A.C. mains transformer. The bias resistance R is taken from a resistance box or a set of wireless resistors.

Using the nominal 100-volt tapping on the H.T. battery, the anode current is observed for about 15 values of R suitably spaced between 0 and 2000 Ω. At each of these values, the negative grid bias $V_g = R \times I_a$ is calculated. Measurements of the same kind are made with H.T. 80 volts and 120 volts. The true values of the H.T. battery voltage should be measured in each case.

From the results, the I_a–V_g characteristics at constant H.T. voltage V can be plotted. These curves are neither the static mutual characteristics (which would show the I_a–V_g relation at constant V_a) nor the dynamic mutual characteristics (which would show the I_a–V_g relation with R constant as an anode load), but they do represent the operating conditions of the valve with bias resistance. It will be noted that the bias necessary for anode current cut-off cannot be reached with this circuit.

Having drawn the curves, the effective valve constants may be found thus: (*a*) Using the curve for the highest value of V, draw a tangent to it at $V_g = -1$ volt and determine the mutual conductance $g = \Delta I_a/\Delta V_g$ at this point; (*b*) taking points on the curves for the highest and lowest values of V used, at 12 mA in each case, calculate the amplification factor $\mu = \Delta V_a/\Delta V_g$ (when I_a is constant). In order to obtain the proper value of V_a, it will be necessary to correct the two values of V for the voltage drop in R in each case; (*c*) the anode resistance R_a is then calculated from $R_a = \mu/g$.

Experiment 52. The Characteristics of a Tetrode or Screen-grid Valve

A tetrode has four electrodes. To convert a triode into a screen grid tetrode, an additional grid is placed between control grid and anode. Its purpose is to reduce the capacitance

between anode and control grid which would otherwise cause a high-frequency amplifying circuit employing a triode to pass into oscillation. The screen grid is kept at a fixed positive potential less than V_a, usually at about 60 volts. Its introduction causes considerable changes in the anode characteristics and constants of the valve. The experiments will show the more important of these changes, of which a short explanation will be given later. We shall use V_s for screen voltage and I_s for screen current.

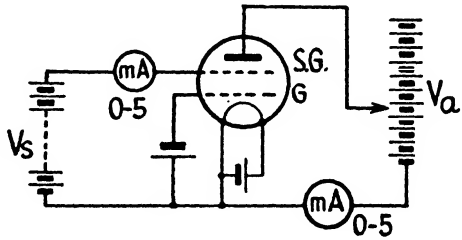

FIG. 68. CIRCUIT FOR ANODE CHARACTERISTICS OF A TETRODE

(a) THE I_a–V_a AND I_s–V_a CHARACTERISTICS

Since the screen is at a positive potential it will take a part of the total space current, the anode taking the remainder. The two characteristics mentioned are therefore intimately related and they may be determined in one experiment. In this experiment V_s is to be fixed at 60 volts and in any set of measurements the control grid voltage V_g is maintained constant. The circuit is shown in Fig. 68, and is the same as that used for determining the anode characteristic of a triode with fixed grid bias, with the addition of a milliammeter (0–5 mA) in the screen lead which is taken to the 60-volt tapping of a H.T. battery. For the purposes of this experiment, a separate H.T. battery for the screen is convenient.

The valve (which may be an Osram S.23) has a top cap which is generally the anode terminal, the screen being connected to the usual anode pin in the base. (The arrangement of the terminals in a multi-electrode valve should always be checked from a catalogue before connecting, as there is no standard practice which is universal.)

Care must be taken that the H.T. lead to the top cap does not fall on to the metallizing of the valve. Before commencing

any measurements, it is advisable to test the various tappings of the anode H.T. battery and to record the values of the voltages for each tapping. This will ensure that no section of the battery to be used is faulty and will give the values for plotting the characteristics.

Setting the control grid bias at $-1{\cdot}5$ volts, and the screen voltage at 60 volts, the anode and screen currents are observed as the anode voltage is increased in small steps from 0 upwards.

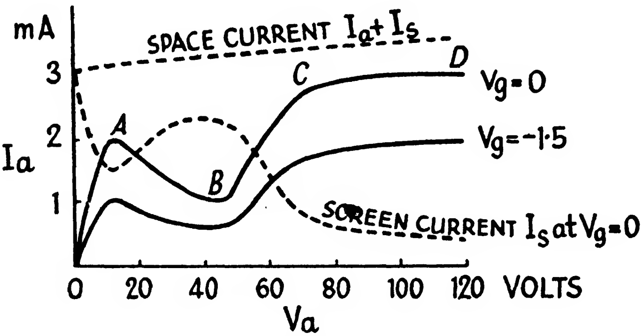

FIG. 69. ANODE CURRENT AND SCREEN CURRENT CHARACTERISTICS OF A TETRODE

These steps should be 6, 12, 18, . . . 120 volts. In order to obtain the smaller values, the negative anode battery lead is taken to the 60-volt tapping, from which these steps upwards may be obtained. After reaching $V_a = 60$ volts, the negative lead is transferred to 0 and the positive to 66, 72, . . . 120 volts.

A second set of readings of I_a and I_s is then obtained at the same values of V_a with $V_g = 0$, i.e. with control grid connected directly to the negative filament terminal.

The I_a–V_a and I_s–V_a characteristics should then be plotted separately, to avoid confusion, although one of the latter, say that for $V_g = 0$, should later be plotted on the I_a–V_a graph so that the relation between I_a and I_s can be shown. The curves will be as shown in Fig. 69. Considering first the straight parts of the I_a–V_a curves such as *CD*, which is the normal operating region with the valve, it will be seen that the anode characteristic resistance R_a $(= \Delta V_a/\Delta I_a)$ is very large. Its value should be calculated. Secondly, using two

points at the same V_a in this region, one on the curve for $V_g = 0$ and one on the curve for $V_g = -1{\cdot}5$ volts, the mutual conductance g $(= \Delta I_a/\Delta V_g)$ is calculated. It will be found to be of the same order as for a triode. Having calculated g and R_a, the amplification factor $\mu = g \times R_a$ is calculated. The large value of μ is one of the most important features of the screen grid tetrode.

The portion AB of the curve, showing a decrease in I_a with increase in V_a, implying a negative resistance, is due

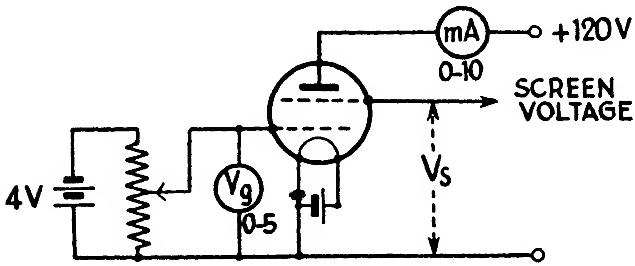

FIG. 70. TO DETERMINE MUTUAL CHARACTERISTICS OF A TETRODE AT VARIOUS SCREEN VOLTAGES

to secondary emission of electrons from the anode and their attraction to the screen when its potential is greater than V_a. Increasing V_a gives greater velocity to the primary electrons which then produce a greater number of secondary electrons. The anode thus loses more electrons than it gains.

Lastly, it will be seen that the screen current I_s alters in a direction opposite to that of I_a as V_a is increased. Adding together I_a and I_s gives the total space current I. This should be done at a few points, giving the dotted curve shown in Fig. 69. The total current is practically independent of V_a, owing to the efficient screening of the anode by the screen grid.

(b) THE MUTUAL CHARACTERISTICS

As for a triode, these show the relation between I_a and V_g, but in the case of the tetrode, the screen voltage as well as the anode voltage is constant for any one curve.

The purpose of this experiment is to show how the mutual characteristics, and hence the value of g, depend on the screen voltage with V_a fixed. The circuit is shown in Fig. 70, V_g being obtained from a potential divider connected across a

4-volt accumulator and measured by a voltmeter (0–5 volts) as in previous experiments. V_a is fixed at 120 volts and the screen voltage is set at 72, 60, and 30 volts in turn.

At each value of V_s, the anode current is measured for control grid voltages $V_g = -4, -3{\cdot}5, -3, \ldots$ up to 0 volts. From the readings, three characteristics are plotted, one for each screen voltage, and the value of g is calculated in each case from the slope of the curve at $V_g = -1$ volt.

The mutual conductance, and hence the amplification factor, will be found to depend on the screen voltage. This is used, in some radio-frequency amplifiers, for controlling the gain of the amplifier by altering the screen voltage.

Experiment 53. The Anode Characteristics of a Pentode

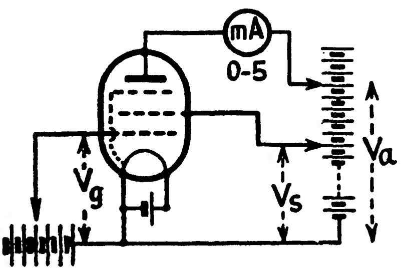

FIG. 71. CIRCUIT FOR ANODE CHARACTERISTICS OF A PENTODE

The addition of another grid between screen grid and anode of a tetrode converts it into a pentode or 5-electrode valve. If this additional grid is connected to the filament, and is thus at the same potential as the filament, the effects of secondary emission, causing the kink in the tetrode characteristics, are absent. The grid is therefore called a suppressor grid. The object of this experiment is to obtain the anode characteristics of such a valve for various values of V_g, the screen voltage V_s being fixed. An Osram W.21 valve will serve for this purpose. It has a top cap, which is the anode terminal, and a 4-pin base, the screen grid being connected to the usual anode pin. The suppressor grid is connected internally to the filament. As with any metallized valve having a top cap, care must be taken to prevent the H.T. lead from falling on to the metallizing. The filament current is supplied by a 2-volt cell.

Before connecting the circuit shown in Fig. 71, the voltages at the various tappings of the H.T. and grid bias batteries should be measured. These are used in place of the nominal values referred to in this description. The anode current is

measured by a milliammeter (0–5 mA) or by an Avometer on a suitable range (which may be changed for those characteristics where the current is small).

Setting V_s at 90 volts, readings of I_a are taken for anode voltages 0, 12, 24, . . . up to 120 volts, with the control grid at $V_g = -6, -4{\cdot}5, \ldots 0, +1{\cdot}5$ volts in succession.

On plotting the $I_a - V_a$ characteristics for the various

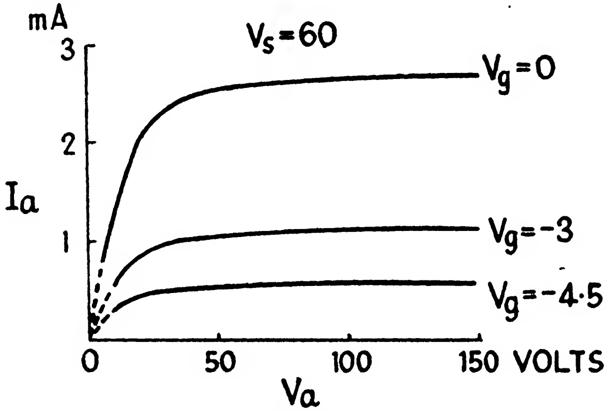

FIG. 72. I_a–V_a CHARACTERISTICS OF A PENTODE

values of V_g, they will be found to have the form shown in Fig. 72. It will be clear that the negative slope associated with the tetrode is absent and that the slope resistance, which should be roughly calculated over the working range $V_a = 90$–120 volts, is very large indeed, I_a being practically constant in this region. The pentode is thus often used as a constant current device. The value of the mutual conduotance g $(= \Delta I_a / \Delta V_g)$ should also be calculated from points on the curves at $V_a = 100$ volts. If this is done for $\Delta V_g = -1{\cdot}5$ to 0 volts and for $\Delta V_g = -4{\cdot}5$ to -3 volts, the two values of g will probably be found to differ, showing that the value of μ depends upon the position of the operating point and on the extent of the swing of grid voltage.

Experiment 54. Mutual Characteristics of a Variable Mu Valve

A pentode may be designed in such a way that the anode current does not have a well-defined cut-off point as the control-grid negative bias is increased, but tails off as larger

negative values of V_g are applied. This is accomplished by making the spacing of the control grid non-uniform.

Such valves are used where it is required to control the amplification by varying the control-grid voltage. An Osram

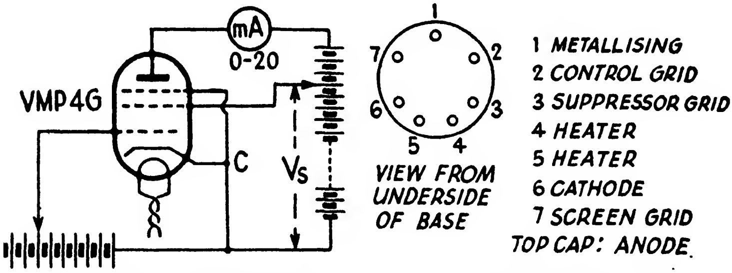

FIG. 73. TO DETERMINE THE MUTUAL CHARACTERISTICS OF A VARIABLE MU VALVE

VMP4G is a valve of this type and its mutual characteristics at various screen voltages are determined in this experiment. This valve is indirectly heated and has a 7-pin base as well as a top cap, so that great care is necessary in connecting up

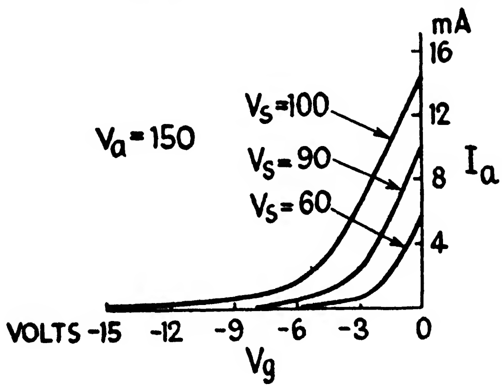

FIG. 74. MUTUAL CHARACTERISTICS OF A VARIABLE MU VALVE

the circuit, shown in Fig. 73, where the base connexions are also indicated, the view being, as in all such diagrams, that obtained by looking at the pins from the *underside* of the base.

It should be noted that each electrode is available at a separate terminal, so that the suppressor grid must be connected externally to the cathode. The heater may be connected to a 4-volt battery or to the 4-volt winding of an A.C. mains transformer. Larger negative grid bias than usual is to be applied, requiring a grid bias battery 0–15 volts, with tappings at 1·5 volts intervals.

Keeping V_a fixed at 120 volts and V_s at 60 volts in the first set of measurements, readings of I_a are made for various grid voltages V_g from 0 to $-$ 15 volts, using each tapping point of the grid battery. This gives one mutual characteristic.

Similar measurements are then made with the screen voltage at 90 volts and at 100 volts, and further characteristics plotted for these cases. They will be of the general shape shown in Fig. 74.

Taking points at $V_g = -$ 6 volts and $-$ 1·5 volts on one of the curves, the value of g at each is found by drawing tangents to the curve at these points and calculating $\Delta I_a / \Delta V_g$ from the slope of each.

Experiment 55. The Characteristic of a Mercury-Vapour Diode

The mercury-vapour diode is used as a rectifier in power packs supplying direct voltage from an A.C. supply when the power required, for a given anode potential, is greater than that which can be handled by an ordinary diode. The valve contains a small quantity of mercury, which, at the low pressure existing in the bulb, vaporizes when warmed by the heating of the filament. When a voltage is applied between anode and filament, the electrons emitted in the ordinary way from the filament move through the vapour with a speed which increases as the voltage is increased. Electrons which have fallen through a potential difference of 10·5 volts or more have sufficient energy to ionize the mercury atoms, knocking out an electron and leaving a heavy positively-charged mercury atom. This process is accompanied by the appearance of a greenish-blue glow in the tube. The positive ions are attracted to the filament and tend to neutralize the space charge round it, thus making available the total emission of the filament to provide the current through the tube. The current is then no longer space-charge-limited and, according to the rating of the valve, may reach 200 to 300 mA.

In using such a valve, two precautions must be observed—

(i) the filament current must be switched on for at least half a minute before applying the H.T., and similarly the H.T. must be switched off first,

(ii) the voltage across the valve must not be allowed to exceed 20 volts, otherwise bombardment by the positive ions will cause the filament to disintegrate.

A large change in anode current takes place when ionization

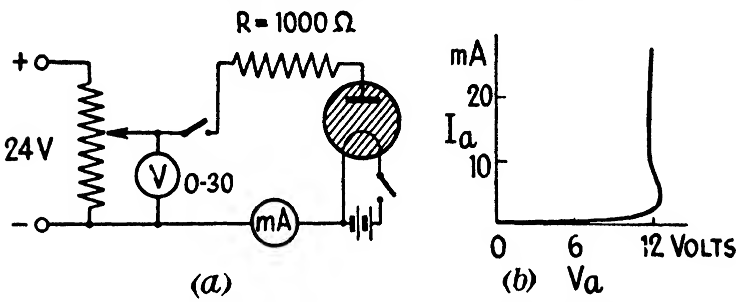

FIG. 75. (*a*) CIRCUIT FOR I_a–V_a CHARACTERISTIC OF A MERCURY-VAPOUR DIODE; (*b*) A TYPICAL CHARACTERISTIC

commences, making it necessary to take great care in the choice of ammeter ranges.

(*a*) THE I_a–V_a CHARACTERISTIC

With this valve, it is essential to use a resistive anode load when determining the characteristic and to calculate the value of V_a as shown below for each value of I_a. The circuit is shown in Fig. 75 (*a*), which applies to an Osram GU50 valve, taking 4 volts on the filament. A rheostat of 1000 Ω capable of carrying ½ amp. forms the anode load *R* and the supply voltage is obtained from a 24-volt battery of accumulators connected to a potential divider from which a fraction is tapped to give *V* volts applied to the valve circuit. For convenience in a later experiment, this potential divider may have a total resistance of 750 Ω capable of carrying ½ amp. Switches should be inserted in filament and anode leads as shown. The reading of *V* must be taken when the anode current is flowing, this current being measured by a universal

meter having several mA ranges, the lowest being preferably 0–1 mA.

Switching on first the filament current and then, after half a minute, the voltage V and starting from $V = 0$, the anode current is measured for values of V up to 12 volts in steps of about 3 volts. The milliammeter range will probably have to be 0–1 mA for the early readings, but the instrument reading must be carefully watched and a higher range switched in as required. From $V = 12$ volts, the steps should be about $\frac{1}{2}$ volt each to $V = 14$ volts and then steps of 1 volt to the 24-volt maximum.

At each value of V, the volts drop V_a across the valve is calculated from

$$V_a = V - I_a \,.\, R - v$$

where $R = 1000\ \Omega$ and $v =$ volts drop across the milliammeter. The resistance of the milliammeter on the various ranges used is therefore required for a precise calculation of V_a, but it will be found that generally v never exceeds 0·1 volt.

On plotting the characteristic, a curve similar to Fig. 75 (*b*) will be obtained. After ionization commences, the voltage across the valve falls slightly with increasing current and then remains constant at about 11 volts.

(*b*) Measurements with Larger Currents

The voltmeter and milliammeter ranges are changed to 100 volts and 100 mA respectively and then, setting V at 0, the 24-volt battery is replaced by the D.C. mains, making sure that the polarity is correct and that the mains leads are connected to the ends of the potential divider, and not to the slider. Corresponding readings of V and I_a are then taken at $V = 0$, 10, 20, . . . 100 volts. In each case the volts drop across the load R is worked out from $V_R = I_a \times R$ and then a graph is plotted to show the relation between V_R and V. It will be found to be a straight line which, when produced backwards to cut the axis of V, will enable the striking potential of the valve to be deduced.

CHAPTER VII

VALVE AMPLIFIER AND OSCILLATOR CIRCUITS AT AUDIO-FREQUENCY

BEFORE proceeding to any measurements with valve circuits, a further examination of the cathode-ray oscillograph is desirable, as this instrument will be used extensively in experiments to be described in this and the following chapters. The Cossor double-beam oscillograph is selected because it appears to form almost a standard part of the equipment of any radio laboratory. This does not imply that other makes are not equally useful for many of the tests.

Experiment 56. The Cossor Double-beam Oscillograph

The main object of the experiment is to observe the use and purpose of the various controls of this oscillograph. A few simple observations are described to illustrate the most important points. As explained in Experiment 34, the chief application is in delineating voltage wave forms.

(*a*) *General.* The supply for the oscillograph is the 230-volt A.C. mains. The intensity and focus of the beams are controlled by the dials marked BRILLIANCE and FOCUS. Deflexions of the spots in the X and Y directions are obtained by applying voltages to the appropriate plates. In the double-beam instrument, deflexions in the X direction are the same for both beams, but the Y deflexions may be controlled independently, an arrangement which is very useful when it is desired to observe two simultaneous quantities such as current and voltage between which a phase difference exists. X and Y deflexions due to external voltages are obtained by connecting these voltages to the X, Y_1, and Y_2 terminals. When the Y_1 and Y_2 terminals are used, the switch at the bottom centre must be turned to PLATES, D.C. or A.C., according to the type of voltage applied. The voltages to be applied to the Y plates may, however, be amplified first by amplifiers contained in the instrument. In this case leads are taken to the A_1 and A_2 terminals (instead of Y_1 and Y_2) and the switch is turned over to AMPLIFIERS, $Y_1 Y_2$.

(*b*) *Horizontal or X Deflexion.* The X SHIFT control moves the spot or trace in the X direction to any desired position.

The remaining X controls are concerned with the *Time Base.* By means of a circuit in which a condenser is charged at a uniform rate and then suddenly discharged, the spot is made to move across the screen from left to right with a constant velocity and then to fly back to its original position. This action is continued and we thus obtain a time base on the X axis. The speed with which the spot moves across is controlled by the switch marked CONDENSER, and by the dial marked VELOCITY, the former giving coarse adjustment by steps and the latter fine adjustment. Increased speed is obtained by turning these controls in a clockwise direction. The extent of the time base is controlled by the dial marked AMPLITUDE. The other time-base controls are those marked TRIGGER and SYN (or synchronizing). TRIGGER varies the time of the flyback and may thus be considered as a very fine adjustment of the velocity. The terminal marked SYN is connected internally to a circuit by means of which a fraction of the applied signal (or voltage) is fed to the time-base circuit and enables the time-base to be synchronized or locked with that signal. The dial marked SYN controls the amount of this feed-back and, in use, should be set at the minimum necessary to achieve synchronization so as to prevent distortion. The SYN terminal should be connected by a link to the Y_1 terminal both when the signal is applied to the Y_1 terminal and when it is applied to the A_1 terminal.

(*c*) *Vertical or Y Deflexion.* The two concentric controls marked Y_1 SHIFT and Y_2 SHIFT move the beams to which they refer in the Y direction as desired. When first using the instrument, see that these controls are set at about the middle of their range; the beams will then be near the centre of the screen. The A_1 GAIN and A_2 GAIN controls affect the gain obtainable with the amplifiers (when the signal is applied to the A_1 and A_2 terminals, with switch at AMPLIFIERS $Y_1 Y_2$). The amplitude of the Y deflexion of both beams is thus controllable.

The other positions of the amplifier switch, viz. AMPLIFIERS $2Y_1$ and $2HF\,Y_1$, are used only when the voltage to be investigated is very small. In the $2Y_1$ position, the two amplifiers are connected internally to form a two-stage amplifier operating on the Y_1 beam only, the signal being applied to the A_1 terminal. At the same time the Y_2 deflexion is available without amplification if desired. For the $2HF\,Y_1$ position

a similar state of affairs obtains except that the anode loads of the amplifiers are adjusted to enable weak radio signals of from 2 to 5 Mc/s to be examined. The gain available in this last position is, however, somewhat reduced. Great care is necessary in using the instrument on these two last-named switch positions.

(*d*) *Additional Controls.* At the top centre of the front panel will be seen a number of sockets marked Y_2 ATTENUATOR, $\times$ 1, $\times$ 2, etc., arranged around a central socket and provided with a small connector link. By setting the connector link between the centre socket and one of the outer sockets, the voltage applied to the Y_2 plates may be reduced to $\frac{1}{2}$, $\frac{1}{4}$, etc., of that on the Y_2 terminal. In normal working the link should be set between the centre and $\times$ 1 sockets.

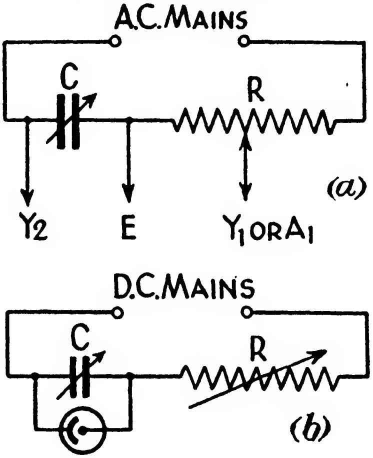

FIG. 76. (*a*) CIRCUIT FOR TESTS ON OSCILLOGRAPH CONTROLS; (*b*) NEON LAMP TIME-BASE CIRCUIT

There are also two sockets marked COILS and provided with a small two-pin plug. These points connect to deflector coils set within the instrument on either side of the tube to give a magnetic deflexion of the beams when it is desired to measure current directly (and not by taking a voltage from the ends of a resistance). No use will be made of the coils in these experiments.

(*e*) *Observations.* After examining the various controls mentioned above, their use may be investigated by fitting up a variable condenser (0–1 μF) and a rheostat (1000 Ω) in series on the A.C. mains as shown in Fig. 76 (*a*), in which the leads are taken to the oscillograph terminals indicated. Tests may then be made of the various controls, in turn, special attention being given to the time-base controls. The phase difference of 90° by which the current through the condenser leads the volts across it may be demonstrated by arranging the two traces to be stationary, with their X axes

coincident and with approximately equal amplitudes, measurements being made on the graph-ruled screen of the "wavelength" of the trace and the displacement of one trace with respect to the other.

Another way of using the oscillograph for investigating voltages with a phase difference of 90° may also be shown with the phase-splitting circuit of Fig. 76. Switching off the time base, the voltages across the condenser and the resistance are applied to the X and Y_1 plates respectively. The trace will then be an ellipse, which may be reduced to a circle by adjustment of the two voltages applied.

(*f*) *A Simple Neon Lamp Time-base Circuit.* Although now replaced by more elaborate circuits, the neon lamp time-base circuit serves to illustrate the principles involved. A condenser is charged from the D.C. mains through a resistance, in this case a subdivided megohm, and is suddenly discharged through the neon lamp when the voltage across it reaches the striking potential of the lamp. The discharge stops when the extinction potential is reached and then the process repeats itself. If the voltage across the condenser were applied to the X plates, a time base would be obtained, the speed of which would depend on the capacitance and the resistance. The ideal voltage for this would have a saw-tooth waveform. It is only approximately so with a neon lamp circuit. Fitting up this circuit, as shown in Fig. 76 (*b*), using $C = 0{\cdot}2\ \mu F$, from a variable condenser and $R = 500{,}000\ \Omega$ from a subdivided megohm, the lamp will be seen to flash intermittently.

The waveform may be investigated by taking leads from the condenser to the E and Y_1 terminals of the oscillograph and adjusting the time base of the oscillograph in the usual way. The effects of altering C and R should be studied, care being taken not to reduce R below $50{,}000\ \Omega$.

Experiment 57. Stage Gain

In a valve amplifier a small alternating voltage V_1 is applied to the grid of a valve and an alternating voltage V_2, generally greater than V_1, is developed across an anode load. At audio-frequency, this load is either a resistance, a low-frequency choke, or a transformer. The ratio of V_2 to V_1 is the *voltage amplification ratio* or *stage gain* and may be represented by G.

In the general case $G = \mu Z/Z_a$ where Z = impedance of the load and Z_a = impedance of the whole anode circuit,

μ being the amplification factor of the valve. Two particular cases will be investigated, the first in which the load is a low-frequency choke and the second in which it is a resistance, the frequency being fixed at 1000 c/s.

In the case of the choke, Z will be very large and nearly equal to Z_a, so that G approaches the value μ. In the case of the resistance, $Z = R$ and $Z_a = R + R_a$ where R_a = A.C. resistance of the valve. Hence $G = \mu R/(R + R_a)$.

In order to obtain amplification without distortion (known as Class A amplification), the operating point must be chosen

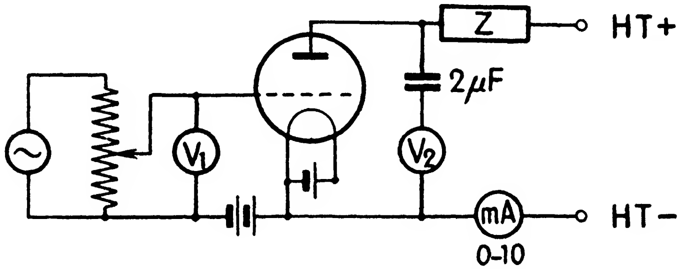

FIG. 77. TO MEASURE STAGE GAIN

so that the grid swing of voltage does not extend beyond the straight part of the I_a–V_g characteristic of the valve. Referring to the characteristics of the H.L.2 valve, which will be used in this experiment, it will be seen that for $V_a = 120$ volts and $V_g = -3$ volts as the operating point, an input V_1, up to about 2 volts (R.M.S.) may be applied without appreciable distortion.

The circuit is shown in Fig. 77, where Z is the anode load. The input voltage V_1 is obtained from a potential divider of 1000 Ω (or a volume control), connected across the terminals of a low-frequency oscillator set at 1000 c/s. V_1 is measured by a Taylor meter set on the 0–10 volt A.C. range and it should be adjusted to be 1 or 2 volts. The output voltage V_2 is measured across Z by a similar instrument on the 0–100 volt A.C. range with a 2 μF condenser in series. This condenser allows only the A.C. component to pass.

With H.T. = 120 volts and a low-frequency choke for Z, the anode current is observed and a test is made to see whether the conditions are those of Class A. If these conditions hold,

the anode current should not alter when the input is switched on. If there is an alteration, the grid bias must be changed or the input voltage reduced. Measurements of V_2 and V_1 are then made for $V_1 = 1$, 1·5, and 2 volts, and the stage gain V_2/V_1 calculated. Its value should be compared with the amplification factor of the valve.

Secondly, a resistance R of 20,000 Ω is used for Z. It will be seen that the anode current is less than with the choke, because of the voltage drop in R. In order to obtain the same operating conditions as before, additional H.T. is required to bring the anode current back to its former value. Measurements are then taken as before and the stage gain compared with the value calculated from $G = \mu R/(R + R_a)$ where R_a is known for the valve or may be found at the time by a simple measurement of anode current for two different H.T. voltages using the valve alone with $V_g = -3$ volts.

A further set of measurements may be made with $R =$ 60,000 Ω.

Experiment 58. Resistance-capacity and Choke-capacity Couplings at Audio-frequency

These experiments are an extension of the previous experiment, their purpose being to investigate the action of two of the couplings used in the audio-frequency amplifying stages of a receiver. Measurements of the gain at various frequencies are to be made in the two cases and the causes of distortion which may arise in their use are to be observed.

Two H.L.2 valves are used, the coupling referred to being that between the valves where R is the resistance and C the capacitance. The circuit is shown in Fig. 78 and may have its principal components mounted on a board, with terminals where necessary, for the connexion of supplies and instruments. Suitable values for the components are shown in the figure. The audio-frequency input is supplied by a low-frequency oscillator, across the terminals of which is a potential divider P consisting of 99,000 Ω and 1000 Ω in series, the tapping to the first valve being from the terminals of the 1000 Ω. A valve voltmeter, $V.V.$, is used to measure the voltage across the whole of P; one-hundredth of it is then the input voltage to the first valve. The H.T. for this valve should be about 160 volts and for the second valve about 240 volts, giving $V_a =$ about 80 volts and 140 volts respectively. The grid

bias is $-$ 1·5 volts on the first and $-$ 4·5 volts on the second valve. As in the experiment on stage gain, the output voltage V_2 is measured by a universal instrument on a 0–100 volt A.C. range connected through a 2 μF condenser to the anode resistance load. In order to investigate distortion, the Y_1 plate of a cathode-ray oscillograph is connected to the end of P as shown and the Y_2 plate to the output terminal, the E terminal being connected to the common negative lead of the circuit.

Commencing with resistance-capacity coupling and having

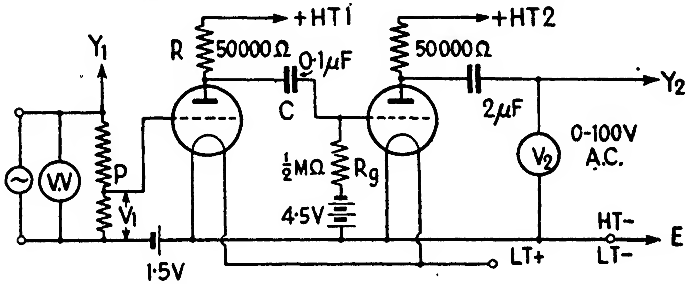

FIG. 78. RESISTANCE-CAPACITY AMPLIFIER

adjusted the valve voltmeter in the usual way, the oscillator is set for some definite frequency, say 1000 c/s, and its volume control is adjusted until the valve voltmeter reading is 10, 20, 30 volts in succession, giving an input voltage $V_1 = 0{\cdot}1$, 0·2, 0·3 volts. At each value, the output voltage V_2 is measured and the gain V_2/V_1 worked out. At the same time the oscillograph traces are observed to ensure that no distortion occurs. Similar readings are then made with frequencies of 100, 200, 500, 5000, and 10,000 c/s. A table should be drawn up showing the gain at various frequencies.

Proceeding to the choke-capacity coupling, the H.T. supplies are first disconnected and R is replaced by a low-frequency choke. The H.T. for the first valve should now be about 80 volts, while that for the second valve remains as before. Observations are made in exactly the same way and a second table drawn up to show the gain at each of the above frequencies.

On examining the results, it will be seen that with resistance-capacity coupling the gain is practically independent of

frequency, while with choke-capacity coupling, the gain increases with increasing frequency but it falls off considerably at lower frequencies. This accounts for distortion due to low-note loss in a receiver.

Tests may then be made on the causes of distortion at a single frequency, say 1000 c/s. Connecting a pair of head-phones in place of the output voltmeter, the effects of over-loading may be studied by increasing the input voltage gradually up to 0·4 volt. At the same time the oscillograph traces will show the distortion which is also apparent in the headphones.

The effect of feed-back from the anode of the second valve to the grid of the first valve, causing instability, may be observed by placing one finger on this grid and another on the output terminal. The feed-back so produced results in "motor-boating."

If the grid resistance R_g is made much larger than the value specified, distortion will also be caused because the time constant of the C–R_g combination is too great.

Experiment 59. Transformer Couplings at Audio-frequency

In this type of coupling, which is frequently used because of the high gain obtainable, the primary of a 1 : 3 or 1 : 5 step-up iron-cored transformer is connected in the anode circuit of the first valve, and the voltage across the secondary is applied to the grid of the second valve. There are two types of transformer coupling, as described below, and measurements should be made with each type.

(*a*) The Series-fed Transformer Coupling

The circuit is shown in Fig. 79. Using the same input arrangement as in the previous experiment, a voltage V_1, equal to one hundredth of that given by a low-frequency oscillator set at 1000 c/s, is applied to the grid of an Osram H.L.2 valve with − 1·5 volts grid bias. The H.T. supply for this valve, in the anode circuit of which is the primary of the coupling transformer, should be about 60 volts. The trans-former secondary is connected to the grid of an Osram P.2 (or similar valve), which is a triode power amplifier, with a grid bias of about − 9 volts, and anode load of 5000 Ω, and a H.T. supply of about 240 volts. As before, the output voltage V_2 is measured by a universal meter set on the 0–100 volt

A.C. range and connected across the load with a 2 μF condenser in series.

A double-beam oscillograph connected to the points marked Y_1, Y_2, and E will show the input and output waveforms and serves to indicate whether there is any distortion. The gain V_2/V_1 of the amplifier is measured for inputs of 0·1 and 0·2 volt at 1000 c/s, and then at 100, 500, and 5000 c/s. The gain at the lowest frequency will be found to be poor.

Observations should also be made of the effect of magnetization of the iron core of the transformer by the direct com-

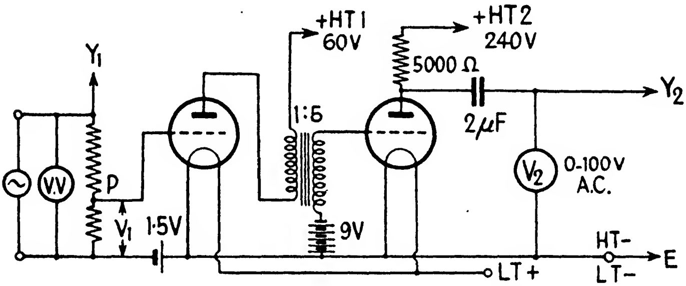

FIG. 79. SERIES-FED TRANSFORMER COUPLING

ponent of anode current. Setting $V_1 = 0{\cdot}2$ volt at 1000 c/s, the H.T. supply to the first valve is increased by steps up to about 100 volts. The oscillograph traces will show the distortion which occurs as magnetic saturation of the core is approached.

(b) THE PARALLEL-FED TRANSFORMER COUPLING

This coupling overcomes the limitation due to saturation of the iron core just mentioned. In effect it is a resistance-capacity coupling feeding the primary of the transformer, the essential changes in the circuit being shown in Fig. 80.

The anode load of the first valve is now 50,000 Ω and therefore the H.T. supply must be increased to about 120 volts. The alternating voltage across this resistance is fed through a 0·1 μF condenser to the transformer primary. No change is needed in the rest of the circuit. Measurements should be made in the same way and at the same frequencies as before, the gain being calculated and compared with that of the series-fed transformer under corresponding conditions.

Experiment 60. The Frequency Response of Transformers

As indicated by the results of Experiment 59, the gain in a transformer coupling falls off at the lowest frequencies. The ideal transformer for coupling would be one giving the same amplification over the whole range of audio-frequencies.

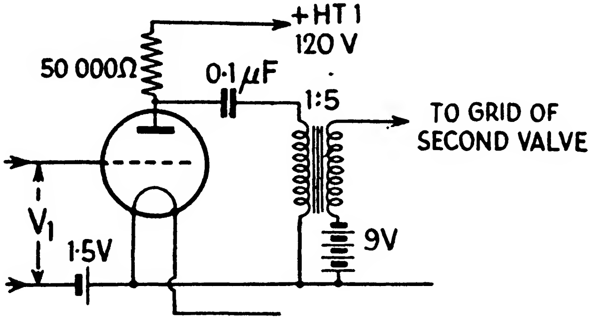

FIG. 80. PARALLEL-FED TRANSFORMER

Although a well-made transformer may approach this ideal, poorer kinds often fall short of it. The frequency response can be investigated by the simple circuit shown in Fig. 81, and, if two transformers are available, one being good and the other poor, it is instructive to compare their performances.

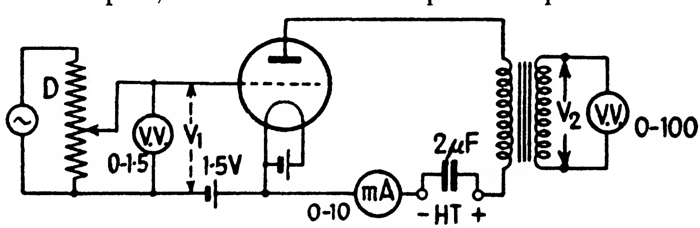

FIG. 81. TO MEASURE FREQUENCY RESPONSE OF A LOW-FREQUENCY TRANSFORMER

An audio-frequency oscillator is used to supply the potential divider D from which an input voltage V_1 of 0·5 volt, measured by a valve voltmeter, is applied to the grid of an Osram H.L.2 valve using – 1·5 volts grid bias. The H.T. voltage is adjusted to give an anode current of about 3 mA. The output voltage V_2 is measured by a second valve voltmeter (0–100

volts) connected across the secondary of the transformer. A 2 μF condenser is connected across the H.T. terminals to by-pass the alternating component of anode current so that it does not pass through the battery.

Measurements of V_2 are taken when V_1 is adjusted to 0·5 volt at frequencies of 50, 100, 200, 300, . . . 1000, 5000, 10,000 c/s in turn. These measurements should be made with a poor and with a good transformer. The results should be exhibited by plotting V_2/V_1 against frequency from 0–1000 c/s and also, on a separate graph, for the range 1000 to 10,000 c/s.

Experiment 61. Matching of Load in an Output Stage

The question of the maximum power which can be provided by a source was considered in a simple D.C. experiment (No. 14) in which it was shown that maximum power is obtained when the load resistance is equal to the internal resistance of the source. This principle of matching is involved in the output stage of an audio-frequency amplifier where the loud speaker is coupled by a transformer to the last valve, the transformer being a step-down transformer in order to deliver considerable current at a low voltage. In the experiment, for which an output transformer is required with two different ratios, say 40 : 1 and 20 : 1, the loud-speaker impedance is represented by a resistance R connected across the transformer secondary. The power in the load is I^2R where I is the R.M.S. value of the current. If the step-down ratio is T : 1, the effective resistance which the transformer gives in the anode circuit of the valve (called the reflected resistance) is $R \times T^2$. The maximum power will be obtained when this is equal to twice the anode impedance of the valve. The object of the experiment is to investigate the variation of output power with load, using the two turns ratios mentioned. The experiments are carried out at a constant frequency of 1000 c/s supplied by an audio-frequency oscillator. Fig. 82 shows the circuit, the valve being an Osram P.2 or Tungsram S.P.220, with a grid bias of $-$ 7·5 volts and H.T. = about 100 volts. The input voltage is measured by a universal meter on a 0–10 volt A.C. range and should be fixed at a steady value of 2 to 3 volts during the experiment. Across the transformer secondary is the resistance R in series with an Avometer on the 0–100 mA A.C. range. R should be variable between 2 and 36 Ω.

Using first the 40 : 1 ratio, R is set at values between 2 and 20 Ω, proceeding by steps of 2 Ω and, at each value, the load current is measured. During this series of readings, the input must be kept constant. The power in watts ($W = I^2R$ when I is in amperes) is calculated for each case and plotted against load resistance R. If the A.C. ammeter has appreciable resistance, this must be included in R. It will be seen that there is a maximum value of W at a particular value of R.

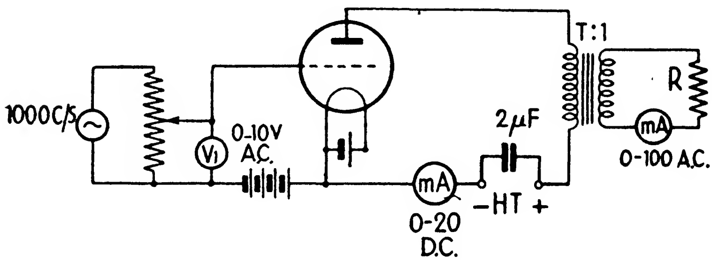

FIG. 82. MATCHING OF LOAD IN TRANSFORMER OUTPUT COUPLING

Calling this value R_m, the effective load resistance, equal to $R_m \times 40^2$, is calculated.

Secondly, similar measurements are made, using the 20 : 1 ratio. In this case the values of R should lie between 4 Ω and 30 Ω. Calculations of W are made as before and the graph showing the relation between W and R plotted. The maximum power will occur at a different value of R. For a 20 : 1 ratio, the effective resistance will be R_m for this case, multiplied by 20^2. It will be seen that the effective loads for maximum power are the same for the two ratios.

Experiment 62. The Efficiency of a Class A Power Amplifier

Amplification under Class A conditions is such as to give an undistorted output. Maximum undistorted output will be obtained when (i) the load is matched as shown in the previous experiment, (ii) the valve is operated near its maximum anode rating, and (iii) the input grid swing does not extend beyond the straight part of the dynamic characteristic. The efficiency is equal to the ratio of output power to input power supplied to the valve from the H.T. battery and is usually expressed as a percentage.

The experiment, therefore, consists in setting up a valve with transformer coupled output under the above conditions and in measuring the input and output powers to obtain the efficiency.

Using the same valve and circuit as in Fig. 82, with the 40 : 1 transformer ratio and with the addition of a cathode-ray oscillograph across R, the value of R is set to that already found for maximum power. This value will probably be about 4 Ω. The grid bias is set at − 15 volts and the H.T. voltage increased to 150 volts. Under these conditions the anode current will be about 15 mA, giving an anode dissipation of 150 × 0·015 = 2·25 watts. The anode rating of the valve is about 3 watts, so that if this has not been reached, the H.T. may be increased slightly to bring the anode power up to nearly 3 watts. Next, the grid input voltage is switched on, starting at a low value, and the cathode-ray trace examined for distortion. The grid voltage is gradually increased until it is the greatest which can be applied without distortion. If Class A conditions are maintained, there should be no change in anode current. Readings are then taken of anode current I_a and secondary current I. The output power is equal to $I^2 \times R$, where R includes the resistance of the A.C. ammeter. The input power is $V \times I_a$, where V = H.T. battery voltage. The ratio of these, expressed as a percentage, gives the efficiency. It will probably not be greater than 20 per cent. If desired, similar measurements may be made with other load resistances, such as 2 Ω and 8 Ω.

In the case of output valves different from those mentioned, the proper operating conditions must be found from the valve characteristics supplied by the makers or determined in separate experiments.

Experiment 63. The Efficiency of Class B and Class C Power Amplifiers

In Class B conditions, the negative grid bias of the valve is increased to the point of anode-current cut-off, while in Class C the bias is increased still further to twice the value for anode-current cut-off. These conditions are not generally used in audio-frequency amplifiers, except in the push-pull arrangement under Class AB conditions, which is the subject of the next experiment, but they are used extensively (especially Class C) in the amplifiers used with radio-frequency

transmitter oscillators owing to the large increase in efficiency which is obtainable. Measurements at audio-frequency can nevertheless be made to illustrate the principal considerations involved.

The anode current in these two cases will consist of a series of pulses which occur at the input frequency. It will contain a number of harmonics in addition to the D.C. and fundamental A.C. components. In order to obtain an output at the fundamental frequency, a tuned circuit, into which the pulses are fed, must be included in the anode circuit of the valve. The anode current then provides the "make-up" current to maintain oscillations in the tuned circuit at its resonant frequency. The efficiency is that of conversion in the anode circuit and is equal to the output power of the oscillatory current at the resonant frequency of the tuned circuit divided by the input power to the anode of the valve. This input power is easily determined by multiplying the H.T. voltage, V, by the mean anode current I_a. To measure the output power accurately is more difficult. If I is the oscillatory current in the tuned circuit, and R the effective resistance of the circuit under the conditions of operation, the output power is $I^2 \times R$. It is the determination of R which is not easy, especially at high frequencies. If the frequency is low, R may be taken, without large error, as equal to the D.C. resistance of coil + ammeter, or it may be measured for the circuit in an experiment similar to that of Experiment 42, by determining Q and using the known values of L and f. The addition of the anode resistance of the valve in parallel complicates the determination at high-frequencies.

It will be clear that if the valve is biased to cut-off, a larger input grid-voltage swing will be possible without reaching the point at which the grid becomes positive. This permissible swing will be still greater under Class C conditions. As audio-frequency oscillators with large voltage outputs are not always available, a 1 : 5 step-up transformer is used to supply the grid input V_1, measured by an A.C. voltmeter on the 0–100 volts range, as shown in Fig. 83. It should be noted that it is the *peak* value of this input which must not exceed the negative grid bias.

If the oscillator is set to give a frequency of 1000 c/s, the anode tuned circuit may consist of a coil of 700 to 1000 turns

and a 0–1 μF variable condenser. A thermo-ammeter of known resistance and of range 0–0·1 amp. should be included in the condenser branch.

Using an Osram P.2 valve with H.T. of about 100 volts, the grid bias V_g is adjusted to Class B conditions (i.e. until the anode current is only just perceptible). The alternating input is then switched on (when there will be an increase in I_a)

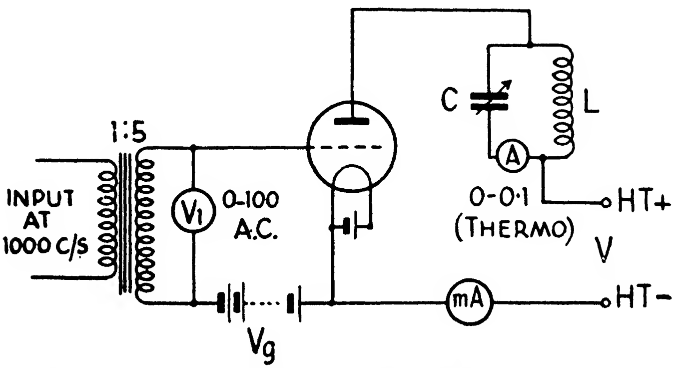

FIG. 83. CIRCUIT FOR CLASS B AND CLASS C AMPLIFIER

and its value adjusted by the volume control of the oscillator until its R.M.S. value is about 0·7 × V_g. The condenser in the anode circuit is then adjusted to give maximum oscillatory current I, and readings are taken of I and I_a. Having measured V, the H.T. battery voltage, the input power $V \times I_a$ is calculated and also the output power $I^2 \times R$, taking for R the D.C. resistance of the circuit, which will be sufficiently accurate in this case. Thus the efficiency is calculated.

Class C conditions are then obtained by increasing the negative bias to twice the value used for Class B, and similarly increasing the grid-voltage swing to about twice its former value. Readings are taken as before and the efficiency worked out. It will be found to be greater than in Class B and much greater than in Class A.

Experiment 64. The Push-pull Output Stage

In the push-pull arrangement two equal alternating voltages 180° out of phase with each other are applied to the grids of

two similar valves connected as in Fig. 84. The outputs of the valves are combined through a transformer having a centre-tapped primary. The advantages of this scheme are given in any standard textbook on radio-circuit theory. As far as this experiment is concerned, the advantages to be noted are that magnetic saturation of the output transformer core is avoided, and that the output is undistorted even under conditions approaching those of Class B, where each valve independently would give considerable distortion.

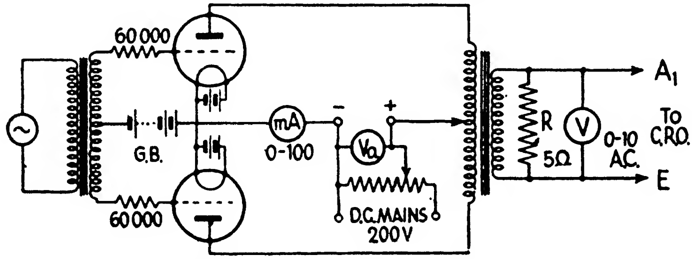

FIG. 84. PUSH-PULL OUTPUT STAGE

Each valve is an Osram PX4, which is a power amplifying triode taking 4 volts on the filament and capable of an anode dissipation of 15 watts, the maximum anode voltage being 300 volts. Owing to the relatively high anode current, the D.C. mains are used for the H.T. supply, using a potential divider as shown. It is also advisable to use separate 4-volt accumulators for each filament as the filament current is large. The input from an audio-frequency oscillator at 1000 c/s is applied to the primary of the push-pull input transformer, which has a centre-tapped secondary and a small step-up ratio. In each grid lead is a resistance of 60,000 Ω to stop parasitic oscillations. On the output side, a 40 : 1 output transformer is used with centre-tapped primary. Across the secondary is a load *R* of 5 Ω, the voltage *V* across which is measured by a Taylor meter (0–10 volts A.C. range). A cathode-ray oscillograph is also connected across *R* for the purpose of investigating distortion. The total anode current is measured by a milliammeter (0–100 mA D.C. range).

(*a*) CLASS A OPERATION

With a grid bias of about − 24 volts, but no input, the H.T. voltage is gradually increased until the anode current

is 60 mA. The oscillator is then switched on and a small alternating input applied, noting at the same time the output voltage and the waveform on the oscillograph. The input is increased until it is just below that necessary to cause distortion. Then anode current I_a, H.T. voltage V_a, and output voltage V are measured. The efficiency is calculated by dividing the output power, which equals V^2/R watts, by the input power, which equals $V_a \times I_a$ watts. It will probably be found to be about 20 per cent.

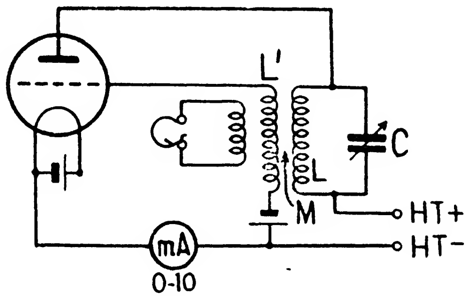

FIG. 85. TUNED-ANODE VALVE OSCILLATOR

(*b*) QUIESCENT PUSH-PULL OR CLASS AB OPERATION

Instead of biasing to anode current cut-off as in Class B, the grid bias is increased to about − 40 volts and the H.T. voltage adjusted, in the absence of alternating input, until the anode current is small, say 5 mA. Proceeding as before, the oscillator is switched on and the input increased until just below that required to cause distortion. Voltages and current are measured and the efficiency calculated as before. The efficiency will be found to be considerably increased, possibly up to 40 per cent.

Experiment 65. A Tuned-anode Audio-frequency Oscillator

One of the important applications of a thermionic valve is its use to maintain electrical oscillations in a tuned circuit. The range of frequencies which a valve can handle is very large, extending from 0 up to 100 Mc/s. The general principles involved in a valve oscillator can be studied at audio-frequency by fitting up a tuned-anode oscillator as shown in Fig. 85. In the anode circuit is a tuned L–C circuit, consisting of a

coil of 700 to 1000 turns, whose inductance should be known, and a variable 0–1 μF condenser. This circuit is coupled to the grid of the valve by the mutual inductance between L and the grid coil L'. If an oscillation is started in the tuned circuit by the switching on of the H.T. supply, a voltage at the oscillation frequency is induced in the grid coil. If this coil is so connected that the phase of the induced grid voltage is such as to cause the initial oscillation to grow by its effect on the anode current, then oscillations are built up and maintained. Their frequency is very nearly the resonant frequency of the tuned circuit, viz. $f = 1/2\pi\sqrt{LC}$. The conditions for oscillation are (i) that the mutual inductance M between L and L' shall be greater than a certain value, depending on the constants of the tuned circuit and of the valve, the condition being $gM > CR + AL$, where C, L, and R are the capacitanee, inductance, and resistance of the tuned circuit and A and g are the anode conductance ($= 1/R_a$) and the mutual conductance of the valve, (ii) that the alternating grid voltage shall be in anti-phase with the alternating component of anode voltage.

The circuit should be fitted up as shown, using a normal small triode, preferably with a large mutual conductance. The coupling coil L' should be of about 1000 turns and should, at first, be kept well away from L. C should be set at 0·1 μF. In order to detect the presence of oscillations a telephone is connected to a third coil which is brought near to L. It is also possible to detect the onset of oscillations by the change in anode current, which usually increases when oscillations commence. Setting the H.T. at a value which gives an anode current of 2 to 3 mA with zero grid bias, the coil L' is brought towards the coil L and the milliammeter is watched for increase of current. If nothing happens, L' is removed and its connexions reversed. Proceeding as before, oscillations will then be set up as L' is brought up. The anode current should not be allowed to exceed 10 mA. Audio-frequency oscillations will be heard in the phones.

Having obtained oscillations, a number of general observations may be made, as follows—

(i) The coupling between L and L' should be reduced and increased again, showing that the mutual inductance between these coils must be sufficiently great if oscillations

are to be maintained. Also, increasing C to, say, 0·3 μF, it will be found that a greater minimum value of M is then required.

(ii) The effect, on the frequency, of altering C is easily observed. As C is increased, the frequency of the note heard in the phones decreases. A point is reached, however, at which oscillations cannot be maintained even with the maximum mutual inductance.

(iii) By adding negative grid bias, say $-$ 1·5 volts, oscillations may be maintained at a lower mean anode current.

Measurements should then be made of the variation of frequency with variation of C. Taking a number of standard tuning forks whose frequencies are known, the condenser C is adjusted until the note in the phones is of the same frequency as the fork in each case, equality of frequency being indicated by the absence of beats. The frequency, f, calculated from $f = 1/2\pi\sqrt{LC}$, is then compared with that of the fork. Alternatively, if L is not known, a graph of C against $1/f^2$ may be plotted, giving a straight line and thus showing that f is proportional to $1/\sqrt{C}$. From the slope of the line, L, which equals $1/4\pi^2 f^2 C$, may be calculated. If C is expressed in farads, L will be in henrys.

Observations may also be made of the oscillatory current in the L–C circuit. Disconnecting the H.T. supply, a universal meter set on the 0–1 ampere A.C. range is connected in series in the condenser arm of the oscillatory circuit. Then, reconnecting the H.T. and obtaining oscillations, a measurement of the circulating current can be made. C should be adjusted to make it a maximum and its relation to the anode current should be noted.

Since the tuned circuit offers a high resistance (its dynamic resistance) to currents at the resonant frequency, the tuned anode oscillator may be considered as a resistance-coupled amplifier which, by reaction, supplies its own input.

Oscillations are maintained when this reaction is sufficient to overcome the damping of the circuit.

CHAPTER VIII

SIMPLE EXPERIMENTS AT HIGH FREQUENCY

Experiment 66. To Construct and Calibrate a Valve Voltmeter

VOLTAGE measurements at high frequency are generally made by means of a valve voltmeter, the advantages of which for this purpose are its very high impedance and the fact that a calibration at low frequency holds for high frequency.

With a triode, use is made of anode-bend rectification by measuring the increase in anode current which occurs when

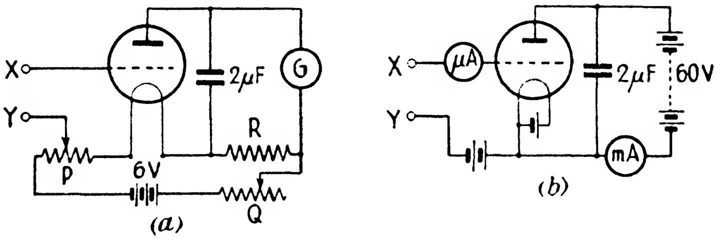

FIG. 86. VALVE VOLTMETER CIRCUITS

the alternating voltage is applied to the grid, so biased that the operating point lies under the lower bend of the I_a–V_g characteristic. Two arrangements may be used, the first being one which does not require a high-tension battery. The circuit for this is shown in Fig. 86 (*a*). The filament of a H.L.2 valve, normally taking 2 volts, has two fixed resistances *R* and *P* in series with it, through which the filament current, supplied by a 6-volt battery and adjustable by the rheostat *Q*, passes. The voltage across *R* supplies the anode voltage for the valve, and that across *P* may be tapped by the slider to provide the requisite grid bias.

Suitable values are $R = 10\,\Omega$, $P = 16\,\Omega$, and $Q = 24\,\Omega$. The anode current is measured by a sensitive galvanometer. A condenser C of $2\,\mu$F is connected between anode and filament to by-pass the alternating component of anode current. The alternating voltage to be measured is applied across XY. There must be a conductive connection between X and Y, as otherwise the grid bias cannot operate.

Another circuit, involving the use of a H.T. battery, is shown in Fig. 86 (*b*). In this case the filament is supplied by a 2-volt cell in the normal way and the grid bias is obtained from a grid-bias battery. A suitable H.T. voltage is about 60 volts, the anode current being measured by a milliammeter (0–5 mA). The voltage to be measured is applied at XY.

Before calibrating, the conditions under which the circuits are to operate are fixed, these being usually such as to give a small anode current when the voltage applied across X and

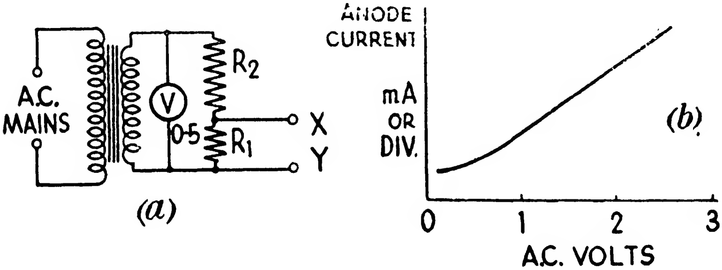

FIG. 87. CALIBRATION OF A VALVE VOLTMETER

Y is zero. Shorting X and Y, the sliders on P and Q in the first circuit are set at their mid position and the galvanometer deflexion noted. If it is more than 1 or 2 divisions, the negative grid bias is increased by adjustment of the slider on P and then, if necessary, the resistance in Q is increased. In the second circuit, the grid bias is set at $-$ 4·5 volts and the H.T. reduced until a current of 0·1 mA is obtained.

Calibration is then effected at 50 c/s by applying to X and Y (having removed the shorting wire) various voltages between 0 and 3 volts (A.C.) from the 4-volt secondary winding of a mains transformer, using a potential divider of constant resistance. The arrangement is shown in Fig. 87 (*a*). Two resistances, R_1 and R_2 in series, such that $R_1 + R_2 = 1000\,\Omega$ are connected across the secondary and leads are taken from R_1 to X and Y. The voltage V across $R_1 + R_2$ is measured by an A.C. voltmeter (0–5 volts) whose accuracy can be relied upon. In the experiment $R_1 + R_2$ is kept constant, so that as R_1 is increased, R_2 is correspondingly decreased. The voltage applied to X and Y is $\dfrac{R_1}{R_1 + R_2} \times V$. Various values

of R_1 are chosen to give approximately 0·2, 0·5, 1·0, 1·5 . . . volts across X and Y, the anode current being read in mA or divisions at each value. The calibration curve is then obtained by plotting anode current against A.C. volts, as shown in Fig. 87 (*b*). If a micro-ammeter (0–100 μA) is included in the grid circuit, as shown in Fig. 86 (*b*), the point at which grid current begins to flow may be observed. The impedance of the valve voltmeter will be reduced under these conditions and if full advantage is to be taken of the high input impedance of the instrument, it should always be used with no grid current.

The above method may be used to calibrate any valve voltmeter in the range 0–3 volts. The accuracy depends, of course, on the accuracy of the transfer instrument (the A.C. voltmeter) used to determine the voltage across the secondary of the transformer. If ranges higher than 0–3 volts are required, the conditions must be altered accordingly. It may be taken as a sound rule, that before using any valve voltmeter, it should be calibrated as above. A calibrating unit, set up on a board, is very useful for this purpose.

Experiment 67. To Set Up and Calibrate an Absorption Wavemeter

A wavemeter is an instrument by means of which the wavelength (λ) or the frequency (f) of high-frequency oscillations may be measured. The simple absorption wavemeter consists of a circuit containing an inductance and a variable air condenser which may be tuned to resonance, the resonant condition being indicated (in this case) by a valve voltmeter. The range of frequencies covered by the wavemeter will depend on the value of the inductance and on the range of the variable condenser. If the condenser range is 0–0·0005 μF, and the coil a 100 turns wireless coil for which L = about $\frac{1}{2}$ mH, the range of wavelengths covered extends from about 400 to about 900 metres. The corresponding frequency range is 750 to 330 kc/s. $\left(f \text{ in kc/s} = \dfrac{300{,}000}{\lambda \text{ in metres}}\right)$

The variable-frequency standard against which the absorption wavemeter is to be calibrated is a standard heterodyne wavemeter having several ranges, for each of which a calibration chart is available. This instrument is a low-power

high-frequency valve oscillator with several ranges, the range desired being selected by a switch and the wavelength being adjustable within this range by a variable condenser. Suitable L.T. and H.T. batteries are required. This wavemeter is coupled to any external circuit by a coupling coil of a few turns at the end of a long twin-flex lead.

The arrangements of apparatus are shown in Fig. 88. The absorption wavemeter with a valve voltmeter (0–5 volts) connected across C is shown on the right and the standard wavemeter on the left. The valve voltmeter is first adjusted

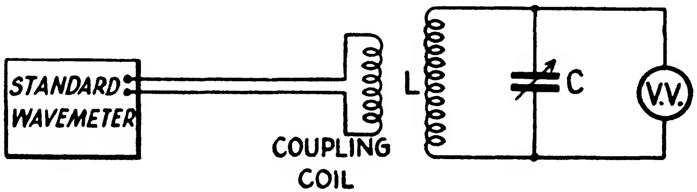

FIG. 88. ARRANGEMENT FOR CALIBRATION OF AN ABSORPTION WAVEMETER

in the usual manner and the coupling coil is set at about 3 in. from the coil L. With C at the mid-point of its range, the standard wavemeter is switched on, with its range selector at the first position. Its condenser is then slowly turned through its whole range, the valve voltmeter being watched for an indication of resonance. If no deflexion occurs, the next range is used and so on, until a deflexion of the valve voltmeter is observed. At this point, the coupling between the circuits should be reduced and the standard wavemeter condenser dial adjusted very carefully until a maximum voltage across the absorption wavemeter is obtained. The wavelength (or frequency) is read from the wavemeter's chart and the setting of the absorption wavemeter's condenser C is observed. This procedure is repeated with C at various settings equally distributed throughout its range, say at 20°, 40°, . . . 180°. From the table of corresponding readings of λ (or f) and C, the calibration curve for the absorption wavemeter is drawn by plotting λ (or f) against the reading of C.

In this experiment, the valve voltmeter is used simply as an indicator of resonance. Other suitable indicators are a neon lamp or a rectifier with galvanometer across C or a low-resistance high-frequency thermo-ammeter in series with

L and C. A simple circuit of the second type, using a diode as rectifier, is shown in Fig. 89. It may be built as a unit, and arranged so that various coils may be used for L, thus providing a number of overlapping ranges.

The valve, which may be a H.L.2 with anode and grid strapped together, is connected across the tuned circuit, the anode current being measured by a microammeter of range 0–500 μA. The calibration of this wavemeter is carried out in the same way as described above, using as small a coupling as convenient and adjusting the standard wavemeter until the anode current is a maximum.

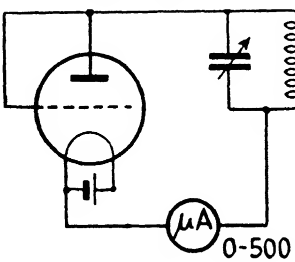

Fig. 89. Simple Diode Wavemeter

Experiment 68. The Variometer

In some high-frequency oscillator circuits, a variable inductance is used for tuning instead of a variable condenser. A variometer consists of two coils so arranged that the inductance is continuously variable over a certain range, while the resistance (which increases with frequency) does not change much. The two coils are joined in series and arranged so that one can be turned inside the other on a common diameter. The change in inductance is due to the alteration in the mutual inductance M between them. When the axes of the coils are at right-angles, $M = 0$ and the total inductance L is simply $L_1 + L_2$, the sum of the self-inductances of the two coils. At any other angle, the value of L depends on whether the action of M opposes or assists L_1 and L_2. If M opposes, then $L = L_1 + L_2 - 2M$, while if M assists, $L = L_1 + L_2 + 2M$. The reason for the factor 2 will be understood if it is remembered that a changing current in L_1 will induce an E.M.F. in L_2, and the same changing current in L_2 will induce an equal E.M.F. in L_1; the effect of M is thus doubled when both coils carry the same current. If the two coils could be made the same size, the minimum value of L would be 0 and the maximum value would be four times the self-inductance of one coil. In practice, since one coil must move inside the other, the minimum L is greater and the maximum L less than these values.

For this experiment each coil may be of 50 turns, the outer coil being about 2 in. in diameter and the inner one slightly smaller, a degree scale 0°–180° being so fixed that the angle between the axes of the coils may be measured. Across the variometer is connected a fixed condenser of 0·0003 μF, the whole forming a circuit which may be tuned by varying the inductance, the wavelength range being approximately 100 to 300 metres.

(*a*) To Calibrate the Variometer-tuned Circuit

As in the previous experiment, a valve voltmeter is connected across the tuned circuit and the coupling coil of a standard wavemeter is brought near to the variometer. Setting the variometer rotor at about the mid-point of its scale, the wavemeter is adjusted, as previously described, until maximum response is indicated by the valve voltmeter. The coupling between the two circuits should be reduced to as small a value as practicable. Proceeding in this way the values of λ (or f) for various settings of the variometer at equidistant points from 0° to 180° over its scale are determined. In particular, the points 0°, 90°, and 180° should be included. The calibration curve, showing the relation between λ (or f) and variometer setting, can then be plotted.

(*b*) Calculation of the Self-inductance and the Maximum Mutual Inductance

The resonant frequency of a L–C circuit is given by $f = 1/2\pi\sqrt{LC}$, from which it may be shown that $\lambda = 1885\sqrt{LC}$ when λ is in metres, L in μH and C in μF. Using this relation (or the frequency relation) the values of L may be calculated at the minimum (0°) and maximum (180°) positions of the variometer if the capacitance of the valve voltmeter (about 10 $\mu\mu$F) and the self-capacitance of the coils are neglected. These values of L are $L_1 + L_2 - 2M$ and $L_1 + L_2 + 2M$, and therefore the difference between them is equal to $4M$ (M being the maximum mutual inductance, occurring when the coils are parallel). Having thus calculated M, the total self-inductance $L_1 + L_2$ may be found.

As a check on this value of $L_1 + L_2$, the value of L at the 90° position may be calculated from the wavelength at this point. $M = 0$ at 90° and thus L for this position is simply $L_1 + L_2$.

Experiment 69. Determination of the Inductance, Self-capacitance, Magnification, and Effective Resistance of a Coil at High Frequency

Two main experiments are necessary in order to determine the above constants of a coil. In the first experiment the resonant frequency (or wavelength) of a circuit containing the coil and a variable air condenser is determined for various settings of the condenser. The standard instruments required are a calibrated high-frequency oscillator or a standard wavemeter, and the calibrated air condenser just mentioned.

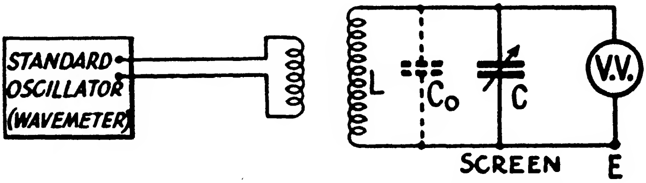

FIG. 90. TO DETERMINE THE SELF-CAPACITANCE, ETC., OF A COIL

In the second experiment this condenser is again required, together with a calibrated valve voltmeter. The two experiments will be considered separately, although the apparatus is practically the same in each. A wireless coil of 100 turns and a variable air condenser of range 0–0·0005 μF are suitable for the measurements.

(*a*) INDUCTANCE AND SELF-CAPACITANCE

If the coil has inductance L and self-capacitance C_0, shown by dotted lines in Fig. 90, while C is the capacitance of the added condenser, the resonant frequency is given by $f = 1/2\pi\sqrt{L(C + C_0)}$ and the wavelength by $\lambda = 1885\sqrt{L(C + C_0)}$. If λ is measured for various known values of C, these equations may be treated graphically, as shown later, to give L and C_0.

The coil and variable air condenser are set up as shown with a valve voltmeter across the circuit as an indicator of resonance. A standard oscillator or wavemeter is set at some distance with its coupling coil near to L, but not too closely coupled. With C at the centre of its range, the wavemeter is adjusted as in Experiment 67, until the voltmeter reading is

a maximum, indicating resonance. This is repeated with the condenser set at various points in its range. Corresponding values of λ (in metres) and C (in $\mu\mu$F) at each setting are found from the calibration charts. The value of λ^2 is calculated and then λ^2 is plotted as ordinate against C as abscissa, as shown in Fig. 91. The plotted points will be found to lie on a straight line which does not pass through the origin, but which makes an intercept OA on the negative axis of C.

OA is a measure of the capacitance which is present in the circuit in addition to C, and C_0 is thus read off. This value includes the capacitance of the valve voltmeter, which may be taken to be 10 $\mu\mu$F and which should be subtracted from the value read from the graph in order to obtain the self-capacitance of the coil alone. The value of L is found from the slope of the straight line. Since $C + C_0 = \lambda^2/1885^2L$, the slope of the line is equal to $1885^2 \times L$. Drawing the right-angled triangle XYZ, the slope is the ratio of XZ, measured in (metres)^2 to YZ, measured in μF. Setting this ratio equal to $1885^2 \times L$ gives the value of L in μH.

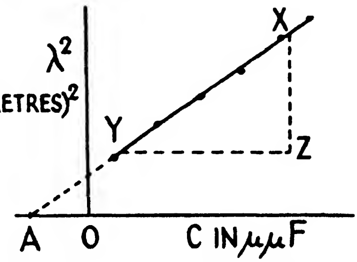

FIG. 91. RELATION BETWEEN λ^2 AND C

(*b*) MAGNIFICATION Q AND EFFECTIVE RESISTANCE R

In order to determine the value of Q ($= \omega L/R$) for the coil, a response curve is determined, using the same apparatus, exactly as in Experiment 42, where the measurement was made at audio-frequency. Setting C at the mid-point of its range, the oscillator is adjusted to the resonant frequency and then C is set at various values on either side of resonance, the reading of the valve voltmeter being taken at each setting. Using the calibration charts of condenser and voltmeter, the voltage V is plotted against the capacitance C. On the response curve, the half-power points, at which $V = 0{\cdot}707$ of the voltage at resonance, are marked. If C = total capacitance at resonance, while ΔC = change in capacitance to pass from one half-power point to the other, then $Q = 2C/\Delta C$.

If the coil has a large value of Q, ΔC will be small and it may then be necessary to include a vernier condenser of much smaller range, say 0–20 $\mu\mu$F, in parallel with C, and to make small changes in C by adjustments of this vernier condenser.

Since $Q = \omega L/R$ and L and Q have been found, R may be calculated if the value of ω at resonance is known. If f is the resonant frequency and λ the corresponding wavelength in metres, $\omega = 2\pi f = \dfrac{2\pi \times 300{,}000}{\lambda}$.

Experiment 70. The Band-pass Filter

When a circuit is required in which the response is the same over a band of frequency, instead of falling off on either

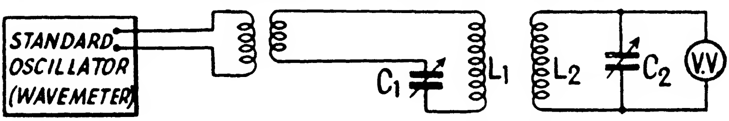

FIG. 92. BAND-PASS FILTER CIRCUIT

side of the resonant frequency as in a simple tuned circuit, two tuned circuits are used, coupled together. The purpose of this experiment is to set up such a circuit and to investigate how the response curve depends on the degree of coupling between the two parts.

Two equal coils, say of 100 turns each, are required for the experiment, and they must be capable of being set at various distances apart so that the coupling between them can be altered. This may be done by using a double-coil holder whereby one coil may be swung away from the other, or by having the coil holders arranged so that they slide along a grooved base, thus keeping the coils parallel. To one of the coils is added a small coupling coil of a few turns set at some distance from the tuned circuits, for the purpose of injecting a voltage into one of them. The coupling coil of a standard wavemeter or oscillator is set near this small coil. Across the inductances L_1 and L_2 are connected variable air condensers (0–0·0005 μF) and a valve voltmeter is available for connexion across either circuit as desired. Setting each condenser at the mid-point of its scale, the wavemeter is switched on and set at approximately the resonant frequency

of each circuit independently, using the valve voltmeter across one circuit while the other is broken. Next, the two circuits must be tuned to the wavemeter frequency more exactly. This cannot be done by connecting the voltmeter to each in turn and then leaving it connected to one circuit for the main experiments. It must be done with the voltmeter connected to the circuit which does not possess the small extra coupling coil, in the following way.

With the L_1–C_1 circuit broken, the wavemeter is coupled directly to the L_2–C_2 circuit and C_2 is carefully adjusted to

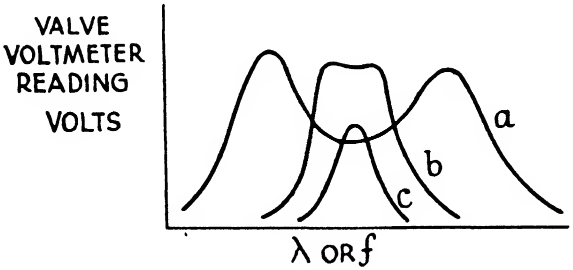

Fig. 93. Response Curves for Coupled Circuits with (a) Tight, (b) Critical, and (c) Loose Coupling

resonance. Then the wavemeter coupling is transferred to the small coil in L_1, the L_1–C_1 circuit is completed and, with a very loose coupling between L_1 and L_2 (i.e. with the coils well separated), C_1 is carefully adjusted until the valve voltmeter across the second circuit indicates resonance.

The main experiments may then be commenced. L_1 is brought near to L_2, say at 2 cm. distance, and the wavemeter condenser dial is moved slowly round over its whole range, thus giving a continuous variation of frequency. The shape of the response curve of the coupled circuits will be shown by the indications of the valve voltmeter and will be seen to be of a double hump form as shown at (a) in Fig. 93. Taking corresponding readings of λ (or f) and response voltage, the curve may be plotted. If the coupling between L_1 and L_2 is too tight, the humps may be separated by quite a large frequency interval.

Similar readings are taken with various values of coupling between the circuits. One coupling should be adjusted to be critical, i.e. at which there is no appreciable double resonance.

This is the band-pass case and the curve will be found to have a flat top as in (*b*). The rapid falling off at each side should be noted in this case. Another coupling should be loose, giving the normal response curve shown at (*c*). This is the case which was used at first to set the circuits to equal frequencies.

Experiment 71. The Tuned-anode R.F. Oscillator

This oscillator circuit is the same as that used for the audio-frequency oscillator of Experiment 65, except that the oscilla-

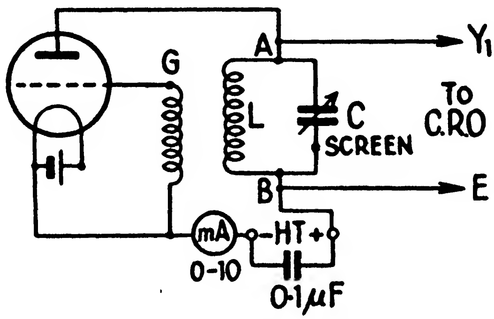

FIG. 94. TUNED-ANODE R.F. OSCILLATOR

tions cannot be detected by telephone. For radio frequencies, the anode and grid coils must have much smaller inductance and the condenser a much smaller capacitance than in the former case. Suitable values are, for the tuned-anode circuit, a coil of 200 turns ($L =$ about 2 mH) and a variable air condenser 0–0·0005 μF, and for the grid coupling coil one of 100 turns.

(*a*) To Set Up the Oscillator and Investigate its Action

The circuit is shown in Fig. 94, the valve being a small triode such as H.L.2. At first, the H.T. supply should not be greater than 40 volts, a 0·1 μF by-pass condenser being connected across it. The two coils may be held in a double coil holder so that the coupling between them may be varied. Across the tuned circuit a cathode-ray oscillograph is connected for the purpose of observing the waveform and amplitude of the oscillations. When the circuit has been set up, the coupling between anode and grid coils is increased slowly;

the milliammeter is watched for any sudden change in anode current, which will indicate the onset of oscillations. If none occurs, the connections to the grid coil are reversed, the H.T. supply being disconnected while this is being done. Oscillations should then be produced on increasing the coupling between the coils, and the time base of the oscillograph should be adjusted to obtain a stationary trace of the waveform containing 3 or 4 complete cycles. The sinusoidal waveform should be noted, indicating freedom from harmonics.

Some general observations on the action of the oscillator may then be made as follows: (i) the effect, on the amplitude and frequency, of altering the coupling between grid and anode coils, taking care that the anode current does not exceed 5 mA; (ii) similar observations with a small and a large value of C; (iii) the effect of touching, in turn, the points marked A, B, and G in the diagram; (iv) the way in which the R.F. voltage across the tuned circuit depends on the H.T. battery voltage. The last-mentioned investigation is carried out by using, in turn, H.T. voltages of 20, 30, 40, 50 volts and measuring, on the oscillograph, the double amplitude from positive peak to negative peak on the trace. The amplitude should be proportional to the battery voltage.

(*b*) Use of Automatic Grid Bias

In order to improve the efficiency of the oscillator, grid bias is required and this is usually provided in an oscillator by connecting to the grid a condenser C_g shunted by a resistance R_g. The condenser is charged by the grid current which flows during the positive half-cycles of alternating voltage in the grid coil, the condenser plate connected to the grid becoming negative. The resistance R_g provides a path by which the charge on C_g may leak, thus preventing the negative potential of the grid from reaching such a value that the anode current becomes zero and the oscillations stop. The arrangement is shown in Fig. 95, a suitable value for C_g being 0·001 μF. With this arrangement, some important effects can be observed by using various values of R_g. Setting $R_g = 60{,}000\ \Omega$, the coupling between anode and grid coils should be increased and the effect, on anode current, of the onset of oscillations should be noted. The coupling may then be increased still further and the effect on current and amplitude observed and compared with the former observations

when no grid bias was used. Observations of the same kind should then be made with $R_g = 20{,}000\ \Omega$ and with $R_g = 1\ \text{M}\ \Omega$. In the last case the charge on C_g cannot leak away fast enough, so that a few oscillations occur which are rapidly damped out and do not recur until the leak of charge from C_g raises the grid potential to the value at which oscillations can start up again, when the process is repeated. This type of action is called "squegging." Finally, removing R_g, the oscillations

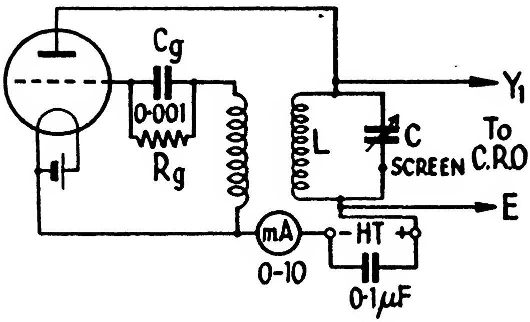

FIG. 95. TUNED-ANODE R.F. OSCILLATOR WITH AUTOMATIC GRID BIAS

will stop altogether unless the insulation resistance of C_g is poor. It is, therefore, preferable to use a mica condenser for C_g.

Experiment 72. Dependence of Wavelength on Capacitance and Inductance in a R.F. Oscillator

In the R.F. oscillator of Experiment 71, the frequency of oscillation may be taken to be the resonant frequency of the tuned-anode circuit, viz. $f = 1/2\pi\sqrt{LC}$, where C includes the self-capacitance of the coil if appreciable compared with the capacitance of the condenser. The corresponding wavelength in metres is given by $\lambda = 1885\sqrt{LC}$ where L is in μH and C in μF. Thus λ is proportional to $\sqrt{C}$ if L is fixed and to $\sqrt{L}$ if C is fixed. The purpose of this experiment is to confirm these relations. A tuned-anode oscillator as shown in Fig. 95 should be set up (omitting the oscillograph) and arranged so that various condensers or various coils can be used in it. At a little distance from the oscillator a heterodyne wavemeter

is set up and its coupling coil brought near to the coils of the oscillator. This wavemeter is provided with a pair of headphones for the purpose of setting the wavemeter frequency equal to that of the oscillator by means of the heterodyne whistle which may be heard when the difference between the two frequencies falls in the audio range.

(*a*) DEPENDENCE OF λ ON C

Three or four small fixed mica condensers of 0·0005, 0·001, 0·002, . . . μF are required. Using an anode coil of about 200 turns and a grid coil of about 50 turns, and commencing with $C = 0{\cdot}001\ \mu$F, the circuit is set into oscillation with the minimum coupling between anode and grid coils. With the wavemeter coupling coil near the oscillator coils, the wavemeter frequency is slowly altered by use of range switches and condenser until a strong heterodyne whistle is heard in the headphones. Then the coupling coil is moved away until the whistle can just be heard and the wavemeter condenser is adjusted until the frequency of the whistle is reduced to zero. If the correct setting for this "dead spot" has been made, the whistle will be heard again, rising in pitch, when the wavemeter condenser is turned either way from this setting. The wavelength corresponding to the setting is obtained from the calibration chart. Measurements of this kind are carried out with various condensers for C, using those mentioned either separately or in series or parallel combination. In this way some ten different values of C may be used.

In order to show the relation between λ and C, λ is plotted against $\sqrt{C}$, when the points should be found to lie on a straight line. With the components mentioned, the self-capacitance of the coil may be 1 per cent of the value of C.

Harmonics are sometimes picked up when tuning the wavemeter, so that a search should be made for the strongest heterodyne note, which will correspond to the fundamental. If there is any doubt, the approximate wavelength can be calculated from the formula given if the value of L is known roughly.

(*b*) DEPENDENCE OF λ ON L

For this experiment, which is carried out in the same manner, a number of coils of known inductance are required,

while C is fixed at 0·001 μF. Suitable coils for L are of 40, 50, 75, 100, and 200 turns, their inductances ranging from about 70 μH to 2000 μH. Using each of these in turn in the tuned-anode circuit and adjusting the grid coupling each time to the minimum to maintain oscillations, the wavelength λ of the oscillations is measured as described in (*a*). A graph of λ for each coil plotted against $\sqrt{L}$ will be found to be very nearly a straight line.

CHAPTER IX

DETECTION AND ALLIED SUBJECTS

DETECTION, or demodulation, is the term given to the process of obtaining an audio-frequency signal from a radio-frequency oscillation on which it has been impressed by modulation. This process of demodulation is effected by rectification, using generally either a diode or a triode. The experiments of this chapter are concerned with detection directly and with arrangements for rendering it more sensitive and selective. Amplitude modulation only is considered. In some of the experiments a R.F. oscillator capable of producing a modulated wave is required. This may be an Avo-oscillator which has 6 different but overlapping frequency ranges from 95 kc/s to 40 Mc/s, and gives an output up to 1 volt. On all ranges it will give either the unmodulated carrier frequency (when the appropriate switch is set at R.F.), or the carrier frequency modulated at about 30 per cent with a single audio-frequency of 400 c/s produced internally (when the switch is set at INT). The oscillator is supplied from the A.C. mains. In order to provide the equivalent of an aerial, two dummy aerials are provided, one marked *ML* for use up to 2·5 Mc/s, containing an inductance and a capacitance of suitable values, and the other, marked *S*, for higher frequencies, containing a resistance. When in use, these are connected in series with the output lead, being screwed into the end of the centre lead in place of the clip which then fits on to the end of the dummy aerial. For further details of the instrument, the instruction booklet issued with it should be consulted.

Experiment 73. Diode Detection

For this experiment, a diode designed for detection is required. A suitable valve is an Osram D.41, which is an indirectly-heated double diode of which only one anode is used. It has a 5-pin base in which the centre pin is the cathode; the normal filament terminals are used for the heater, while the two anodes are connected to the usual grid and anode pins. The heater requires 4 volts, which may be taken from cells or from the 4-volt secondary winding of a

mains transformer. Fig. 96 shows the complete circuit for the various sections of the experiment. The output from the oscillator is fed through the *ML* dummy aerial to a tuned *L–C* circuit, across which is a valve voltmeter. The tuned circuit may consist of a 100-turns coil and a variable air condenser up to 0·0006 μF. The voltage across the tuned circuit at resonance is applied between anode and cathode of the valve, with an anode load (shown here in the cathode

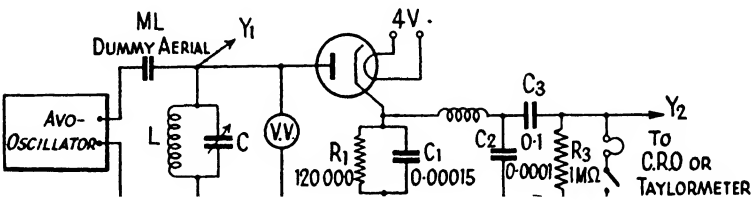

FIG. 96. CIRCUIT FOR DIODE DETECTION

lead) which consists of a resistance $R_1 = 120{,}000\,\Omega$ and a capacitance $C_1 = 0{\cdot}00015\ \mu$F in parallel.

The rectified output is obtained across this load and passes on to the circuits shown on the right of it, which are filters by means of which only the audio-frequency component is obtained. This part of the circuit consists of a high-frequency choke (H.F.C.) and a condenser C_2 (0·0001 μF) which stop and by-pass the radio-frequency component, the condenser C_3(0·1 μF) which blocks the D.C. component and a resistance R_3 of 1 M Ω, across which the audio-frequency component is obtained and may be observed in the phones or on the oscillograph or may be measured by a Taylormeter on a suitable A.C. voltage range. The two last-named instruments may also be required for connexion across other parts of the circuit.

Having connected and arranged the circuit so that its various parts are easily identified, the following observations should be made—

(1) With the filter circuit disconnected, and with the oscillator set to give unmodulated R.F. output, the condenser *C* in the *L–C* circuit is set at the mid-point of its scale and resonance is obtained, as indicated by the valve voltmeter, by adjusting the oscillator frequency. The waveform of

the R.F. is observed on the Y_1 beam of the oscillograph connected across the tuned circuit. At the same time, a *D.C. voltage* is developed across the diode load R_1C_1 and this may be measured by the Taylormeter (on a D.C. voltage range). Then, turning the oscillator switch to give the modulated R.F. output, its waveform may be observed across the tuned circuit, using a lower time-base frequency on the oscillograph. The D.C. voltage, measured across the load as before, will be found to be unchanged provided the input voltage across the tuned circuit is unchanged.

(2) The filter circuit should then be connected across the diode load. The audio-frequency output across R_3 is observed, first by phones and secondly on the Y_2 beam of the oscillograph. By comparing the traces of the Y_1 and Y_2 beams (Y_1 being connected to the tuned circuit), it will be seen that the audio-frequency is that of modulation. Next, disconnecting phones and oscillograph from R_3, the audio-frequency voltage across this resistance should be measured by the Taylor meter on a suitable A.C. voltage range. Various values of modulated R.F. input voltage from 20 to 5 volts (as measured on the valve voltmeter) should be obtained by detuning the oscillator, and at each, the output voltage across R_3 should be measured. An approximately linear relation will be found to exist between input and output voltages.

(3) Reconnecting the oscillograph across R_3, observations should be made of the distortion in audio-frequency waveform which arises if the diode load resistance is too great. The waveform with $R_1 = 1$ MΩ should be compared with that already obtained when R_1 was equal to 120,000 Ω.

Experiment 74. Anode Detection

In anode detection, the signal, magnified by a tuned *L–C* circuit, is applied to the grid of a triode so biased that the operating point lies under the lower bend of the I_a–V_g characteristic. The changes which take place in the anode current when the signal is applied are as follows—

(i) If the signal is an unmodulated R.F. oscillation, the mean anode current rises and contains a D.C. component and R.F. components. The latter cannot be heard in phones, the only effect being a click when the signal is applied or switched off.

(ii) If the signal is a modulated R.F. oscillation, then the anode current contains, in addition to the above components, a component at the audio-frequency of modulation, which can then be heard in the phones.

The circuit is shown in Fig. 97. The tuned circuit consists of a coil L of 100 turns and a variable air condenser C of about 500 $\mu\mu$F (max.). This circuit is connected to an aerial with a variable air condenser C_1 of 300 $\mu\mu$F (max.) in series. The signal across the tuned circuit is applied to the grid of

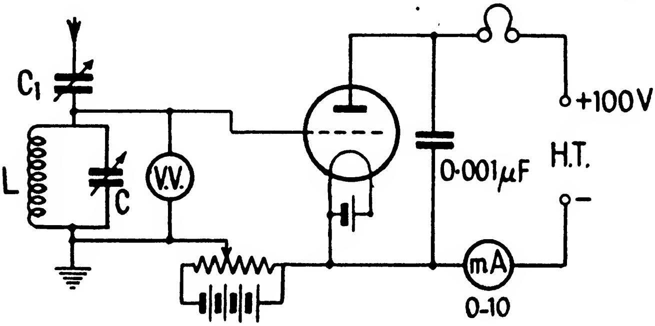

FIG. 97. CIRCUIT FOR ANODE DETECTION

an Osram H.L.2 valve, in which the negative grid bias is continuously adjustable between 0 and − 6 volts, by means of a potential divider of 100 Ω connected across a 6-volt accumulator.

A pair of headphones is connected in the anode circuit and the R.F. components of anode current are by-passed by the 0·001 μF condenser between anode and filament. For the experiments, a H.T. voltage of 100 volts is suitable.

With the aerial disconnected, the grid bias is adjusted until the anode current as shown by the milliammeter is small, say 0·2 mA. Then the aerial is connected and the condensers C and C_1 adjusted to give maximum reception of a broadcast programme. The tuning with C should be found to be fairly sharp, since no grid current is flowing and the tuned circuit is therefore not damped on this account. Observations of the change in anode current when the signal is received should be made.

The effect of altering the grid bias may also be investigated, using the phones and changing the bias by means of the potential divider. It will be found that the adjustment for optimum reception is fairly critical. The bias should be set at this value.

Further observations may then be made on the selectivity and on the effect of the aerial condenser C_1. For this purpose a valve voltmeter is connected across the L–C circuit, observations being made with the voltmeter and with the phones at the same time. The selectivity may be measured by the change in C required to reduce the alternating voltage applied to the grid to half-value, the selectivity being greater the smaller this change in C. If C_1 is then reduced, the effective aerial capacitance, which is in parallel with the tuning circuit, is reduced and a larger value of C is required for resonance. This reduction in C_1 causes a decrease in signal strength at resonance, but the selectivity is improved, as may be shown by measuring the change in C required to reduce the voltage to half its value at resonance. Measurements of this kind should be made at several settings of C_1.

Instead of using an aerial, the modulated R.F. output of an Avo-oscillator may be used as in the experiment on diode detection.

Experiment 75. Grid Detection

In grid detection, the modulated signal, after magnification by a tuned circuit, is applied between grid and filament of a triode with a condenser C_g shunted by a resistance R_g in the grid lead. The grid-filament part of the valve acts as a diode detector, grid current flowing on the positive half-cycles and building up a voltage across the "diode" load R_g–C_g. This voltage gives to the grid a potential which is negative and which becomes more negative as the amplitude of the carrier increases. The valve as a whole then acts as an amplifier of this grid voltage. If the signal is an unmodulated R.F. oscillation (continuous wave, C.W.) the anode current falls when the signal is received and contains a D.C. component and R.F. components only. If the signal is modulated at audio-frequency, the anode current also falls on reception, but contains, in addition to the above components, a component at the modulation frequency which may be heard in the phones.

The circuit of Fig. 98 may be used to show the main features of grid detection. The signal may be obtained from an aerial with a condenser C_1 in series as in Experiment 74, or from an Avo-oscillator with the dummy aerial ML included as in Experiment 73. The advantage of the latter is that an unmodulated or a modulated oscillation may be obtained as desired. The tuning coil L of 100 turns should be provided with tappings at, say, 80 and 60 turns, shown at the points 2 and 3 in the diagram. C is a variable air condenser up to 0·0006 μF. Suitable values for the grid condenser and

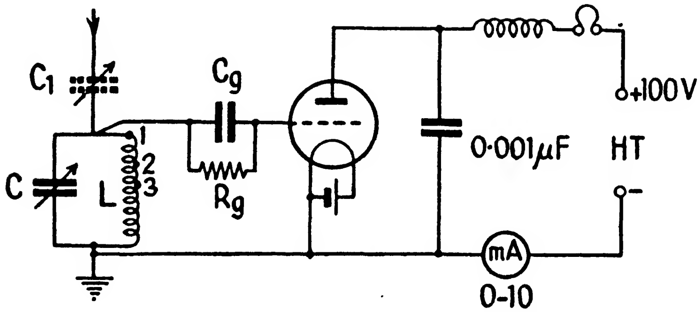

FIG. 98. CIRCUIT FOR GRID DETECTION

resistance are $C_g = 0{\cdot}0003$ μF and $R_g = 1$ MΩ. If a subdivided megohm is available for R_g, the effect of altering its value to 0·5 and 0·25 MΩ may be studied. The valve is an Osram H.L.2 with a 0·001 μF condenser between anode and filament to provide a by-pass for the R.F. components of anode current, and with a high-frequency choke and phones in the anode circuit, which is supplied by a H.T. battery of about 100 volts. A milliammeter (0–10 mA) shows the anode current.

In a first set of observations, the aerial condenser is not included. The anode current is noted before tuning in to the signal and then again after tuning. A decrease, which is characteristic of grid detection, will be observed. If an oscillator is used, the observations should be made first with carrier only, and secondly with the modulated oscillation. The selectivity should be examined by detuning C. It will be found to be poor compared with that of the anode detector because of the damping effect of the grid current.

Improvements in strength of reception and in selectivity may be obtained by the following modifications—

(i) The grid condenser and resistance are connected to a tapping point on L. The grid current now flows through part of the tuning coil only and the damping effect should be reduced. Each tapping point should be tried in turn.

(ii) The aerial condenser C_1 is included and adjusted for maximum reception.

(iii) The end of the grid resistance R_g farthest from the grid is connected first to the negative filament terminal (earth), and secondly to the positive filament terminal. The latter connexion gives the grid a small positive bias, thus ensuring a flow of grid current, which is essential to the operation of the detector.

One important method of improving the selectivity is to use reaction. This is the subject of the following experiment.

Experiment 76. Reaction

In the valve oscillator (Experiments 65 and 71) the coupling or reaction between grid and anode coils is increased until it is sufficient to overcome completely the damping of the tuned circuit. In a grid-detector circuit, reaction obtained in the same way but adjusted to be less than that required for self-oscillation, is used to increase the signal strength and to decrease the damping of the tuned circuit, thus increasing both the sensitivity and the selectivity of the receiver. The amount of reaction may be controlled by adjusting the distance between the grid and anode coils, as in the oscillator, or, as is more generally the case, by the use of a condenser in conjunction with a coil in one of the ways to be described. It may also be controlled by altering the anode potential.

The first reaction circuit is that shown in Fig. 99. It is the same as that for grid detection, with the addition of the coil L_2 and the variable air condenser C_2 connected in series between anode and earth. Instead of the aerial, an oscillator giving a modulated R.F. output is coupled to L_1 by a coil of 50 to 100 turns. The signal input can be increased or decreased by placing this coil nearer to or farther from the tuned circuit, or by altering the volume control of the oscillator. If L_1 and L_2 are fixed in an adjustable double-coil holder, with L_2 connected in the correct sense, all the above-mentioned

controls of reaction may be investigated. Suitable values for the components are $L_1 = 100$ turns, $L_2 = 30$ to 50 turns, $C_1 = 0{\cdot}0006\ \mu F$ (max.), $C_2 = 0{\cdot}0004\ \mu F$ (max.), with other component values as shown in the diagram; the valve is any detector, such as an Osram H.L.2. Opening C_2 and moving L_2 away from L_1, the tuned circuit is adjusted to resonance, with a signal of about 500 kc/s, the audio-frequency of modulation being heard in the phones. The input coupling should then be reduced to give a weak signal. Bringing L_2 nearer to L_1, the reaction will be increased as shown by the increased

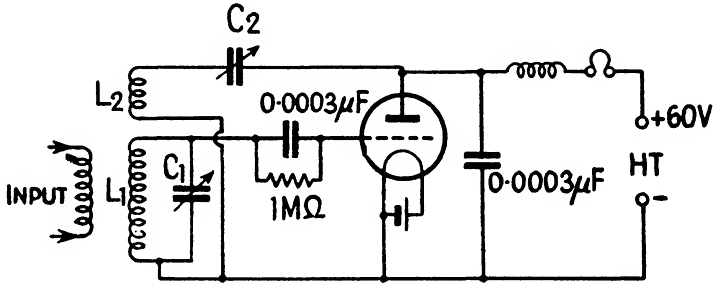

FIG. 99. FIRST REACTION CIRCUIT

strength of signal and it may then be still further increased up to the point of oscillation by increasing the capacitance C_2. The coupling between L_1 and L_2 should be arranged so that the circuit goes in and out of oscillation smoothly at about the mid-point of this condenser.

Anode potential control may be shown by setting C_2 to give some reaction and then increasing the H.T. voltage from 60 volts by steps, noting the increase in signal strength and eventual oscillation.

A further test should be made to see whether an increase in reaction (short of oscillation) makes it necessary for the L_1–C_1 circuit to be retuned.

The increase in selectivity which accompanies the use of reaction should also be tested. The range of C_1 over which the signal can be heard is noted, first with little or no reaction and then with increased reaction. The sharper tuning when reaction is used will be obvious and is due to the reduction in damping of the tuned circuit.

Where condenser control of reaction only is required, the

coil L_2 may be wound on the same former as L_1 or may be part of it. The circuits of Fig. 100 show two other types of condenser control, which may easily be set up by slight modifications of the circuit just used. Tests similar to those mentioned may be made with these circuits. In (*a*) the condenser C_2, instead of being in series with L_2, is in parallel

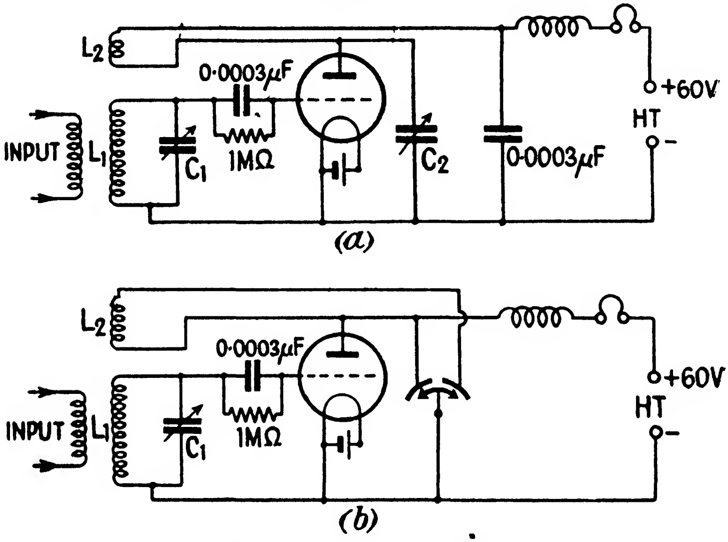

FIG. 100. SECOND AND THIRD REACTION CIRCUITS

with L_2 and the usual by-pass condenser. The reaction, in this case, will be increased by decreasing C_2.

In (*b*) a differential condenser replaces C_2 and the by-pass condenser of Fig. 99. The advantage thus gained is that the total capacitance between anode and earth is constant, and the tuning of the L_1–C_1 circuit will not be affected by increasing the reaction.

Experiment 77. Heterodyne and Autodyne Reception

The methods of detection used for a modulated wave are of no value for receiving continuous wave, as was shown in the experiments on detection. Continuous wave (C.W.) is used for wireless telegraphy, employing Morse signalling, and its reception is carried out by the heterodyne method. Into

the tuned circuit of the receiver, tuned to the signal frequency f_1, there is injected from a local oscillator a signal of frequency f_2, whose value differs from f_1 by a small amount, say 1000 c/s, which is within the audible range. When these two signals are applied to a rectifier, such as a grid detector, the anode current contains a component whose frequency is the difference between f_1 and f_2 and is therefore audible.

If the transmission at f_1 is made in a series of dots and dashes, the heterodyne beat note will occur in a similar series of signals. When the second frequency is provided by a separate local oscillator, the method is called heterodyne reception. When, however, this frequency is provided by setting the receiving circuit into oscillation, the method is called autodyne reception. Each of these types can easily be set up with the apparatus of the previous experiment with the addition of a second R.F. oscillator for the heterodyne case.

(*a*) To show heterodyne reception, the circuit of Fig. 99 is fitted up, but without reaction. A tapping key may be placed in the input lead which comes from the R.F. oscillator providing the signal at f_1. A second oscillator of the same kind is arranged with its coupling coil near to L_1. The L_1–C_1 circuit is first tuned to f_1. This may be done by using the first oscillator alone to give a modulated oscillation and then turning the switch over to give C.W. The second oscillator is then brought into operation and its frequency f_2 adjusted to be near f_1. The heterodyne note will be heard in the phones and it will be noted that there are two settings of f_2 which will give a note of a particular beat frequency, one greater than f_1 and the other less. Setting this beat note at about 1000 c/s, the key in the input circuit may be operated to imitate a Morse signal. It should be specially noted that neither f_1 nor f_2 can be heard alone and that the heterodyne note can be obtained only if both f_1 and f_2 are passed through a rectifying device.

(*b*) For autodyne reception, the second oscillator is removed and the reaction circuit of the detector is brought into play. With the adjustment at f_1 as before, the reaction is increased until the circuit passes into oscillation. If C_1 is slightly detuned, the frequency f_2 of this oscillation will be different from f_1 and the heterodyne beat note will be heard. Observations similar to those in (*a*) may then be made.

Experiment 78. The Triode-hexode Frequency Changer—The Principle of Super-heterodyne Reception

If, in the previous experiment on heterodyne reception, the signal frequency f_1 and the local oscillator frequency f_2 had been widely different, say by 100 kc/s, the anode current of the detector would have contained a component at this difference frequency, but it would have been beyond the audible range and would have been a R.F. oscillation of a frequency $(f_1 \sim f_2)$ much lower than f_1. This changing of the frequency from a high to a lower value (but still sufficiently high to be used as a carrier frequency) is the basic principle underlying super-heterodyne reception, the difference frequency being called the intermediate frequency (I.F.). Any modulation carried by f_1 is passed on to the I.F. oscillation and may then be detected in the usual way. In super-heterodyne reception the I.F. has a fixed value which is obtained from any signal which it may be desired to receive, by adjustment of the local oscillator frequency.

The triode-hexode valve is a multiple valve in one envelope which provides the triode for the local oscillator and a hexode by means of which the I.F. is provided from the signal frequency f_1 and the oscillator frequency f_2 by electron mixing. The hexode contains a control grid to which f_1 is applied and an injector grid to which f_2 is applied. This injector grid is joined internally to the grid of the triode and is provided with a screen on either side. The valve used is an Osram X.24 which takes 2 volts on the filament and has a 7-pin base, the connexions of which are shown in Fig. 101. Considering first the local oscillator circuit, giving f_2, this is a simple tuned grid oscillator, the two coils for which are wound on a small cylindrical former with the coils taken to the pins of a 4-pin valve base, the arrangement being that shown in the diagram. These coils should be shielded by an earthed metal case. The tuning condenser, across the grid coil, is of maximum value 0·0005 μF. In order to limit the oscillator anode current, a resistance of 20,000 Ω is included in the H.T. lead. Considering now the hexode-mixer valve circuit, the signal at f_1 is fed to the control grid, which, it should be noted, is the top cap. A steady voltage of + 60 volts is applied to the screens, and a screen condenser of 0·1 μF connected between them and earth. In the anode circuit of the hexode is the I.F. transformer which consists of two equal resonant circuits with

coils having an iron-dust core for permeability tuning by adjustment of a small air gap in the core. The resonant frequency of either circuit is the I.F. which, in a type commonly used, is 465 kc/s. In the experiment, a valve voltmeter and a cathode-ray oscillograph are connected across the secondary of this transformer, the leads to these instruments

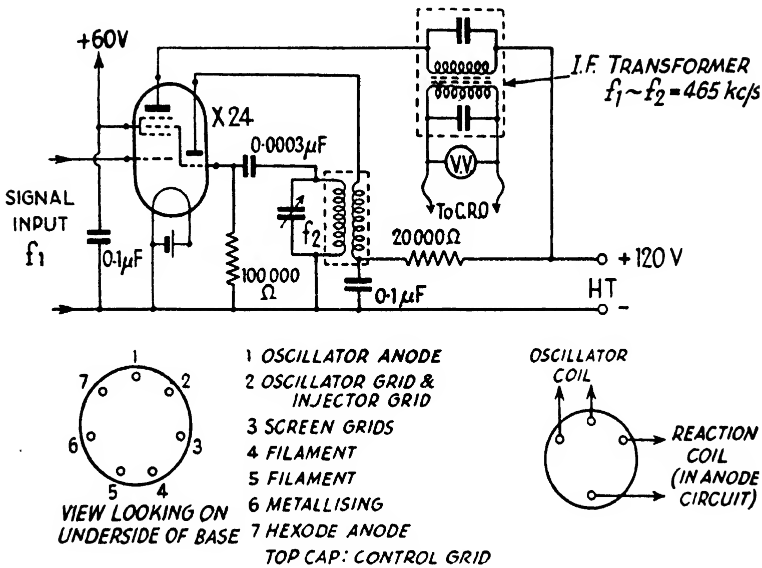

FIG. 101. TRIODE-HEXODE FREQUENCY-CHANGING CIRCUIT

being kept untwisted and as far apart as possible to avoid interference with the transformer tuning owing to their capacitance. When connecting the circuit, the shortest possible leads should be used. The values of the various components are shown in the diagram.

In order to obtain the intermediate frequency, the following adjustments are made—

(i) A signal from the R.F. oscillator only, set at the I.F. of 465 kc/s is applied to the control grid of the hexode and the I.F. transformer is tuned by adjustment of the dust core until a maximum reading of the valve voltmeter, indicating resonance, is obtained.

(ii) Switching off the R.F. oscillator and connecting the local oscillator, the condenser of the latter is adjusted until the valve voltmeter again gives a maximum reading. This adjustment ensures that the local oscillator is functioning and it also gives the reading of its condenser for the I.F. of 465 kc/s, which needs to be avoided in the later observations.

(iii) Using both oscillators, the signal input frequency f_1 is set at 600 kc/s; and then the local oscillator frequency f_2 is adjusted to give maximum voltage in the I.F. transformer secondary. The oscillograph is used to show the waveform of the I.F.

Two points will be noted in this setting of the local oscillator, first that the setting at 465 kc/s is not used, and secondly that there are two settings which will give the I.F., one for which $f_2 = 1065$ kc/s, and the other for which $f_2 = 135$ kc/s.

Having thus obtained the I.F., observations may be made with a modulated input and on second channel interference. The R.F. oscillator is set to give a modulated input at 600 kc/s and the waveform of the I.F. observed with the oscillograph time-base frequency at a lower value than in (iii). It will be seen that the I.F. carries the modulation of the input signal. In order to show second channel interference, the local oscillator is set at its higher value to give the I.F. (i.e. $f_2 = 1065$ kc/s) and the signal input frequency is then changed from 600 kc/s to approximately 1530 kc/s, which is as far above f_2 as 600 kc/s is below it. By slight adjustment of the signal oscillator, the I.F. will again be observed. Thus there are two signal frequencies which will give the same I.F. for a particular setting of the local oscillator. In addition to the observations mentioned above, the occurrence of heterodyne notes in the audible range should also be examined. The hexode anode circuit contains, in addition to the I.F., a number of other frequencies such as f_1, f_2, $f_1 + f_2$ and their harmonics. These are not shown on the oscillograph because the I.F. transformer is tuned to $(f_1 \sim f_2)$. Their presence may be shown by including, in the anode lead, a pair of phones. Keeping f_2 fixed, the signal frequency is slowly varied, when a number of heterodyne whistles will be heard. These occur whenever the signal frequency or one of its harmonics differs from the local oscillator frequency or one of its harmonics by an amount lying in the audio-frequency range.

Experiment 79. Radio-frequency Amplification—The Tuned-Anode Coupling

When a weak signal is to be received, amplification at the radio-frequency is employed before detection. R.F. amplification usually requires that a single frequency be amplified to the exclusion of other signals. Tuned circuits are therefore used, one of the commonest being that in which a tuned coupling is placed in the anode circuit of the amplifying

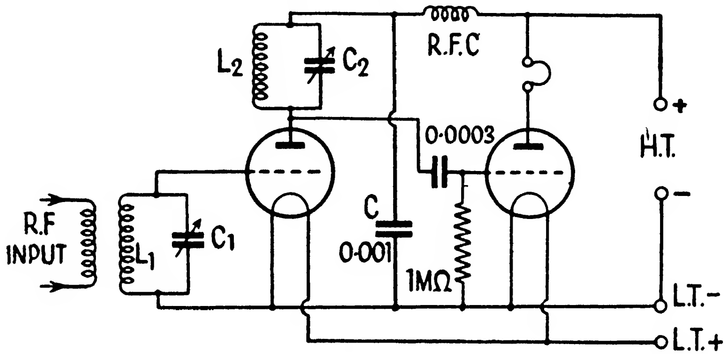

FIG. 102. TUNED-ANODE R.F. COUPLING

valve, in a position similar to that of the resistance or choke in audio-frequency couplings. Difficulties arise in R.F. amplification owing to the tendency of the amplifying valve circuit to pass into oscillation, and to the coupling which may occur from the R.F. voltage set up across the internal resistance of the H.T. supply. The first difficulty is overcome by the use of a S.G. tetrode, and the second by the use of decoupling resistances and condensers. In this experiment a tuned-anode circuit is to be set up and its action investigated, using first a triode and secondly a S.G. tetrode, so that a comparison between them may be made.

The first circuit is shown in Fig. 102. A R.F. oscillator, giving a modulated wave, is coupled to the tuned L_1–C_1 circuit of the first valve (Osram H.L.2). In the anode circuit of this valve is the tuned L_2–C_2 circuit, exactly similar to L_1–C_1, the amplified voltage across this circuit in the anode being taken to the second valve (also an H.L.2) acting as a grid detector.

The two coils should be fixed some distance apart with their axes at right angles to avoid direct coupling between the two tuned circuits. In the anode lead of the first valve, the R.F. choke prevents the R.F. currents from passing through the H.T. battery and the fixed condenser C (0·001 μF) provides a low impedance path for them to earth. The coils L_1 and L_2 may be of 100 turns each and the condenser C_1 and C_2 variable up to 0·0005 μF. These condensers should be set at their mid-points to begin with.

Switching on a modulated R.F. oscillation at about 500 kc/s, the following tests should be made—

(i) The L_1–C_1 circuit is tuned for reception. By varying C_1 over a small range, the intensity and selectivity of the circuit is noted.

(ii) The L_2–C_2 circuit is now tuned. A marked increase in selectivity, shown by the sharper tuning of C_1, will be apparent. Adjusting C_1 and C_2 alternately, the maximum intensity should be obtained. The reception is then much more sensitive and selective, as may be shown by reducing the input and taking observations at various settings of C_1 and C_2.

(iii) Returning to conditions for maximum intensity, the condenser C is removed. The reception immediately falls off, owing to lack of decoupling of the H.T. supply.

(iv) If the amplifier valve circuit passes into oscillation, as it may do owing to coupling between the anode-tuned circuit and the grid-tuned circuit through the anode-grid capacitance of the valve, a heterodyne whistle will be heard. This tendency to oscillation is overcome by the use of a S.G. tetrode.

For comparison with the above circuit, a similar circuit using a tetrode should be fitted up, the connexions being those shown in Fig. 103. Some alteration in wiring will be necessary if the tetrode anode is the top cap. Apart from this and the addition of the screen voltage of + 60 volts, and the screen condenser of 0·1 μF, the circuit is the same as before, with the same components. Tests similar to those made previously are carried out.

The advantages which follow from the use of a tetrode are the increased sensitivity due to the high amplification factor of the valve and the greater stability arising from the lower

anode-grid capacitance which reduces the tendency to break into oscillation.

The above tests may also be made with an aerial in place

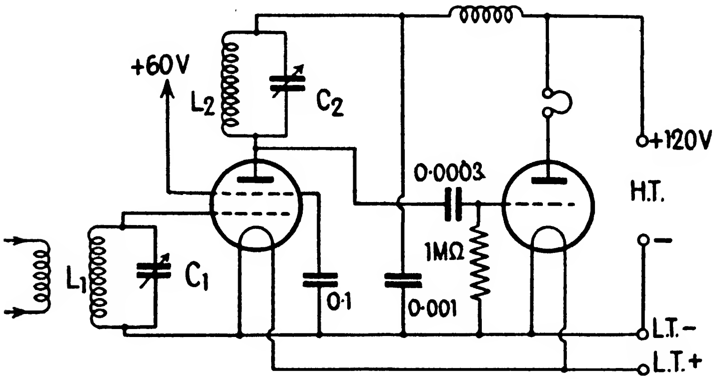

FIG. 103. TUNED-ANODE COUPLING USING A TETRODE

of the R.F. oscillator, the reception being of a broadcast programme. In this case an aerial tuning condenser may be included and its effect observed in addition.

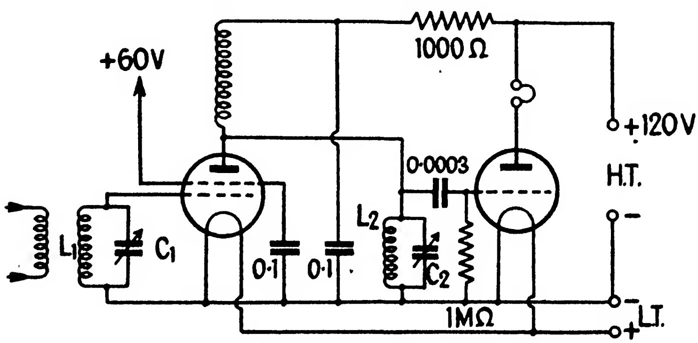

FIG. 104. TUNED-GRID R.F. AMPLIFIER

Experiment 80. The Tuned-grid Coupling

This is another type of R.F. coupling, the circuit for which is shown in Fig. 104. It consists effectively of a tetrode acting

as a R.F. amplifier with choke-capacity coupling to the tuned grid of a grid detector.

The anode load of the tetrode is a R.F. choke, the other components having the same values as for the tuned-anode circuit of the previous experiment. A decoupling resistance of 1000 Ω is included in the H.T. lead to the tetrode. Setting the variable condensers at their mid-points at first, tests may be made of sensitivity and selectivity as with the tuned-anode amplifier. It will be found that, although the sensitivity appears to be as good as in that case, the selectivity is less sharp. This is due to the damping of the L_2–C_2 circuit by the grid current of the detector. In order to obtain better selectivity, the circuit may be varied by taking the lead to the detector grid condenser from a tapping on L_2, so that grid current passes through a portion only of the tuned circuit and does not impose so large a damping effect.

CHAPTER X

TRANSMITTER CIRCUITS

APART from the aerial, the principal circuits used in a transmitter are the oscillator, the amplifier, the modulator, and the circuit for frequency control. Illustrative experiments on each of these are included in this chapter. The valves and components used are not, however, of the size and power which are employed in actual transmitters, but are adapted to the conditions of a laboratory experiment.

The types of oscillator circuit used in transmitters differ usually from the tuned-anode oscillator of Experiment 71, and three of the principal types will be considered first.

Experiment 81. The Series-fed Hartley Oscillator

In the Hartley circuit, the feed-back necessary for maintaining oscillation is obtained, in the correct phase, by including part of the inductance of the tuned circuit in the grid circuit of the valve and part in the anode circuit by using a tapping point on the coil. The series-fed arrangement, in which the tuned circuit and valve are supplied in series from the H.T. battery is usually preferred to the parallel-fed arrangement owing to the tendency of the latter arrangement to produce parasitic oscillations. The Hartley circuit is generally used for frequencies in the higher ranges. In the diagram of Fig. 105, the coil is shown tapped at a number of points in addition to the tapping point referred to above. This enables the point of connexion of the anode lead (the anode tap) to be chosen for the most efficient operation. *L* is a coil of about 60 turns wound on a cylinder 2 in. in diameter and *C* is a variable air condenser up to 0·0003 μF. A thermo-ammeter (0–0·5 amp.) indicates the oscillatory current and a milliammeter (0–40 mA) records the anode current. The valve may be an Osram P.2 or a similar type, taking 2 volts on the filament and 150 volts (max.) on the anode.

The presence of oscillations is shown by bringing a separate coil of a few turns connected to a pea lamp near to the coil *L*, when the lamp will glow if the circuit is in oscillation. The frequency of the oscillations is measured by a wavemeter

of the heterodyne or of the absorption type, using a loose coupling.

Having obtained oscillations with the variable condenser at its mid-point, a series of measurements should be made of oscillatory current and anode current for different positions of the anode tap, keeping the capacitance fixed. It will be seen that there is a position in which the oscillatory current is strongest. Similar measurements should be made with a smaller and with a larger value of C, and the results compared.

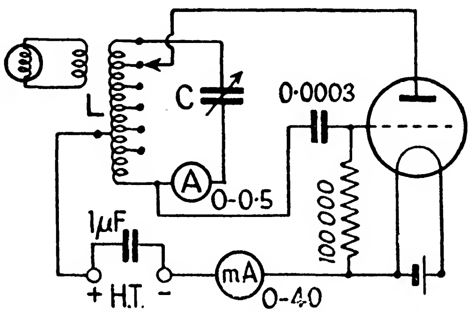

FIG. 105. SERIES-FED HARTLEY OSCILLATOR

Secondly, the oscillator should be calibrated. The frequency is measured by means of the wavemeter at a number of settings of C over its whole scale, the anode tap being adjusted at each to give maximum oscillatory current. The calibration chart, showing the relation between the frequency and the reading of C should then be plotted.

As in all valve oscillators where the grid bias is provided by a grid condenser and resistance, the performance will depend on the value of grid resistance used with a particular valve. Some tests should be made on this point by using various grid resistances, say 20,000 Ω, 100,000 Ω, 500,000 Ω, and 1 M Ω.

Experiment 82. The Colpitts Oscillator

This circuit is usually employed for frequencies in the lower R.F. ranges. The grid drive is obtained by tapping the capacitance of the tuned circuit instead of the inductance as in the Hartley circuit. Across the tuning condenser C are connected two small condensers C_1 and C_2 in series, as shown

in Fig. 106, the common terminal of these being connected to the negative filament terminal. The inductance L may be that of a coil of 100 turns, C may range up to 0·0006 μF and the values of C_1 and C_2 may be 0·00005 and 0·0001 μF respectively, so that about one-third of the voltage across C is fed to the grid. The passage of R.F. oscillations through the H.T. battery is prevented by the R.F. choke and the 2 μF by-pass condenser.

As in the previous experiment, the presence of oscillations

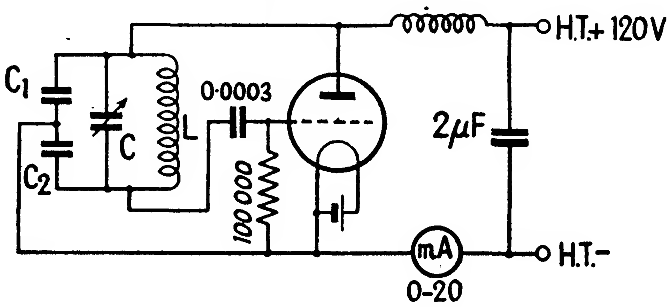

FIG. 106. THE COLPITTS OSCILLATOR (PARALLEL-FED)

is observed by a pea lamp connected to a small coil brought near to L. The grid condenser and resistance are the same as for the Hartley oscillator. It should be noted, however, that in the Colpitts circuit it is essential that the grid resistance be connected from grid to negative filament terminal, whereas in the Hartley circuit it might equally well be connected across the grid condenser.

Having obtained oscillations with the circuit, the frequency calibration curve may be constructed, using an absorption or a heterodyne wavemeter with loose coupling to measure the frequency at various settings of C. Further observations may be made of the changes in anode current at the onset of oscillations and also of the effect of changing the grid resistance.

Although not used perhaps as often as other types of oscillator, the Colpitts circuit illustrates how a divided capacitance will give the conditions for oscillation. This divided capacitance may arise, in the absence of external condensers, in the valve itself, the various portions being the capacitances

between anode and filament, between anode and grid, and between grid and filament. The inter-electrode capacitances limit the upper frequency which may be obtained with a valve oscillator circuit of the normal type.

Experiment 83. The Tuned-anode—Tuned-grid Oscillator

Two tuned circuits are used in this oscillator, one in the anode circuit and the other in the grid circuit of the valve. The coupling between them, necessary for the maintenance

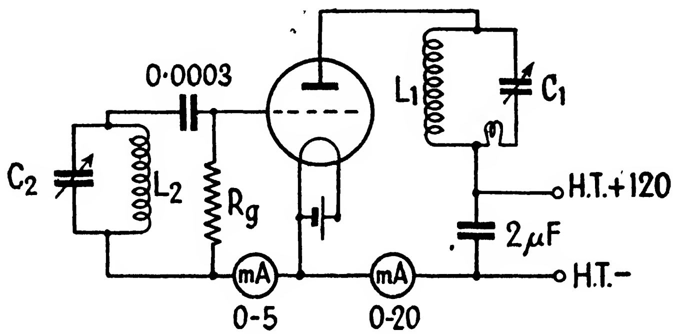

FIG. 107. SERIES-FED TUNED ANODE–TUNED GRID OSCILLATOR

of oscillations, is obtained through the anode-grid capacitance of the valve, the coils being set therefore at some distance apart to reduce the mutual inductance between them. A series-fed oscillator of this type is shown in Fig. 107, the two tuned circuits being alike, each consisting of a coil of about 50 turns and a variable air condenser up to 0·0003 μF. The valve may be an Osram P.2 or similar type. The frequency of oscillation is that of the anode L_1–C_1 circuit and the maximum oscillatory current in this circuit, as shown by the flash-lamp connected in the circuit, is obtained by adjustment of the condenser in the grid L_2–C_2 circuit. In addition to the usual milliammeter (0–20 mA) for anode current, a second instrument (0–5 mA) is placed in the grid circuit to show the value of the grid current. Using first a grid resistance R_g of 20,000 Ω and setting C_1 at its mid-point, the grid condenser C_2 is adjusted to give the strongest oscillations as shown by the flash-lamp. The changes which take place in anode current and in grid current as this adjustment is carried out should

be noted. Similar adjustments and observations may be made for different settings of C_1 and also for different values of grid resistance, say 100,000 Ω and 1 M Ω.

By coupling a heterodyne wavemeter to the anode coil and adjusting it to give a heterodyne note in its phones, any change in frequency which occurs on adjusting C_2 may be observed. If the frequency alters, the pitch of the heterodyne whistle will change.

An attempt should also be made to investigate whether

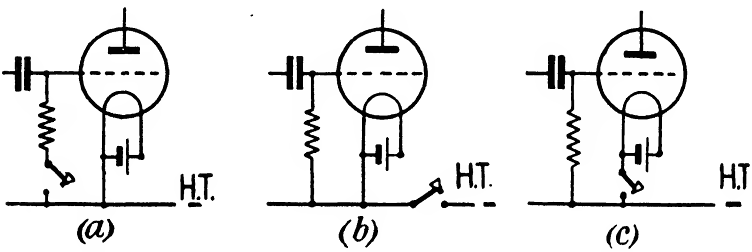

FIG. 108. VARIOUS WAYS OF KEYING A TRANSMITTER

the circuit will oscillate on the self-capacity of the coils alone, by removing C_1 and C_2.

A modification of the tuning arrangements may be made if two equal variometers are available. In this case each tuned circuit would consist of a variometer with a fixed condenser of 0·0002 μF across it and the tuning would be carried out by adjusting the variometers.

KEYING A TRANSMITTER

For the purposes of wireless telegraphy, a transmitter must be keyed so that the transmission is interrupted as desired to send out a Morse signal. Direct keying can be used only on the low potential side and the various ways in which this may be done are shown in Fig. 108. They should be tried in turn, using any one of the oscillators which have been described, first removing the meters from the circuit. In order to observe the effects of keying, a heterodyne wavemeter should be coupled to the oscillator and adjusted to give a heterodyne note, the wavemeter then acting as an autodyne receiver.

At (*a*) in the diagram is shown one form of grid keying by which the grid resistance connexion is broken and the grid

assumes a larger negative potential, causing oscillation to cease. At (*b*) the key is in the negative H.T. lead, thus cutting off the H.T. supply when it is opened. The best method, however, is that shown at (*c*), where the key is placed between the negative H.T. terminal and the negative filament terminal (or cathode). In this cathode keying, the grid assumes the negative potential of the H.T. battery when the key is opened.

The transient effects which arise when the key is opened or closed cause the frequency to change considerably during the short intervals of time concerned. This change in frequency will be obvious in the wavemeter phones. These transient effects limit the rate of signalling which is possible with the simple keying arrangements described.

Experiment 84. The Master Oscillator-Power Amplifier System

In a transmitter, the oscillator is not used to supply the power to the aerial. The function of the oscillator circuit (called the master oscillator) is to provide a constant radio frequency. Its output, which is relatively small, is fed to a power amplifier arranged to throw a very small load on the oscillator. This amplifier is adjusted to work under Class C conditions and is neutralized to prevent it from passing into oscillation. The use of a pentode instead of a triode makes neutralization unnecessary, but few transmitters are supplied with power amplifiers employing pentodes.

The purpose of this experiment is to set up a master oscillator-power amplifier circuit and to adjust the power amplifier to the conditions mentioned above. Fig. 109 shows the circuit. On the left is a series-fed Hartley circuit which constitutes the master oscillator. Its output is fed through a 0·001 μF condenser to the grid of the valve of the power amplifier shown on the right. The tuned-anode circuit of the amplifier is exactly similar to that of the oscillator, the inductance being centre-tapped. This enables a voltage to be fed back to the grid, through the neutralizing condenser C_N, in anti-phase with the feed-back which occurs through the anode-grid capacitance. This is the Hazeltine method of neutralization, the capacitance C_N being adjusted until the two anti-phased voltages are equal in magnitude. This condenser should have a range of about 60 $\mu\mu$F. Suitable coils for L_1 and L_2 are of 100 turns each, centre-tapped. C_1 and C_2

are variable air condensers up to 0·0003 μF. The two valves are of the type Osram M.H.4, which is an indirectly-heated valve taking 4 volts on the heater. In the grid circuit of the amplifying valve are a R.F. choke and a D.C. milliammeter (0–10 mA) to measure the grid current. Steady negative bias is applied to the grid which, for efficient operation of the amplifier, is to be driven positive for a portion of each cycle. The H.T. supply for each valve is 200 volts, and if this

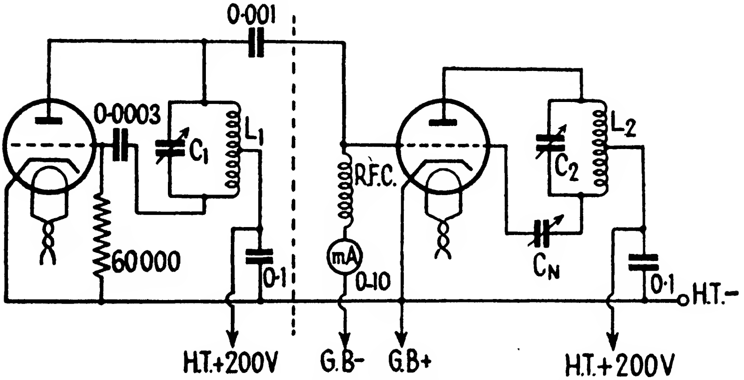

FIG. 109. MASTER OSCILLATOR—POWER AMPLIFIER SYSTEM

is taken from the D.C. mains, care must be taken to obtain the correct polarity and in handling the wires.

Having obtained oscillations in the master oscillator circuit with C_1 at its mid-point, the grid bias of the amplifier is adjusted to Class C conditions. With the valve and H.T. voltage mentioned, anode cut-off occurs at V_g = about − 8 volts. The grid bias is therefore set at − 16 volts and the grid current observed. If this is greater than 1 mA the negative bias must be increased. The adjustments for resonance in the tuned circuit of the amplifier and for neutralization are then carried out by one of the following methods. *With the amplifier H.T. supply switched off*, a valve voltmeter or oscillograph is connected across L_2, and resonance is obtained by adjusting C_2 with C_N at its zero setting, the circuit being fed through the anode-grid capacitance of the valve. Then C_N is adjusted to reduce the voltage across the circuit at resonance to zero. In the second method, use is made of grid

current changes, also with H.T. supply disconnected. Resonance is obtained by adjusting C_2 with C_N at zero, until a sudden change or kick in the reading of the grid-current meter is observed, the reading of C_2 being noted. Then C_N is adjusted until no such kick occurs when C_2 is adjusted through resonance. This gives neutralization and C_2 is reset at its position for resonance.

Experiment 85. Modulation

Amplitude modulation consists in a variation, at audio-frequency, of the amplitude of the R.F. (or carrier) wave. In order to obtain this, the R.F. oscillatory current in the anode circuit of the power amplifier of a transmitter is caused to vary in amplitude and this may be accomplished in one of two ways, either by causing the anode potential to vary at audio-frequency or by causing the grid potential to vary at audio-frequency. In this experiment, simple circuits will be set up to show each method of modulation and their performance will be examined by the cathode-ray oscillograph. The oscillation to be modulated is provided by a R.F. oscillator giving a steady output, such as an Avo-oscillator, and the modulating frequency is provided by a L.F. oscillator which can be set to give various frequencies at a voltage which can be adjusted.

If A is the amplitude of the modulating wave while B is the amplitude of the carrier wave, the depth of modulation is measured by A/B, usually expressed as a percentage. If the modulated wave has a maximum amplitude L and a minimum amplitude S, then the depth of modulation is equal to $(L - S)/(L + S)$. The latter formula can be used when the modulated waveform is observed on an oscillograph with its time base set to show, say, two complete cycles of the audio-frequency of modulation.

(a) Anode Modulation

The circuit is shown in Fig. 110. The output of the R.F. oscillator is connected to a potential divider of 500 Ω (or a volume control) from which a tapping is taken to the grid of the valve. An Osram P.2 valve is suitable. A negative grid bias of 6 to 9 volts is required with H.T. supply = 120 volts. The L.F. oscillator output is connected to a second potential divider from which a tapping is taken to the primary

of a 1 : 3 step-up L.F. transformer, the secondary of which is included in the anode circuit in series with the H.T. supply as shown. The anode circuit also contains a coil of about 400 turns which is coupled magnetically to another coil of about the same number of turns to which the oscillograph is connected. A condenser of 0·001 μF by-passes the R.F. First, with L.F. oscillator switched off, the R.F. is set at about 200 kc/s and the input to the valve adjusted until the

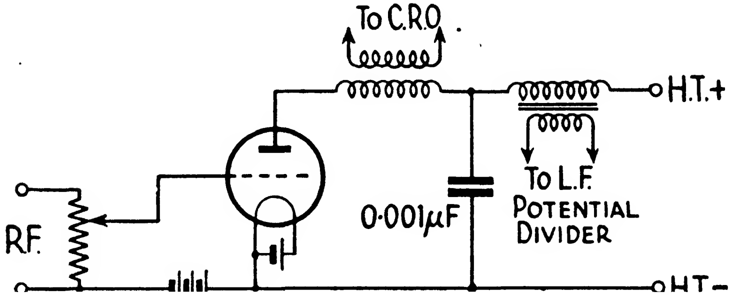

FIG. 110. ANODE MODULATION CIRCUIT

waveform shown on the oscillograph is of reasonable amplitude, using a medium coupling between oscillograph and anode circuit. The time-base frequency is then reduced until the trace is merely a band across the screen. A modulating voltage is then applied from the L.F. oscillator at, say, 1000 c/s and gradually increased by adjustment of the potential divider, the oscillograph time-base being adjusted to show a few cycles of the modulating frequency. At some stage, measurements of the maximum double amplitude and minimum double amplitude should be made and the percentage modulation calculated by the formula already given. If the modulation depth is increased, distortion will be observed, and, if it is possible to obtain a percentage modulation greater than 100, it will be seen that there is no R.F. oscillation during a portion of the modulating cycle.

(b) GRID MODULATION

The arrangement for grid modulation is shown in Fig. 111, the modulating voltage being injected into the grid circuit. In order to avoid an excessive grid swing of voltage, a step-down

transformer is used. Adjustments and observations are made in a manner similar to those for anode modulation. Although, in some respects, grid modulation is easier to arrange, as it does not involve such large L.F. voltages, it

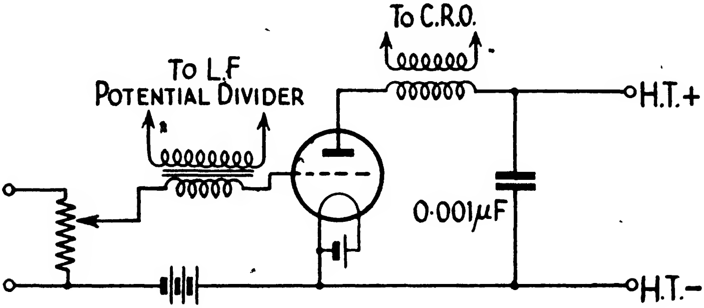

FIG. 111. GRID MODULATION CIRCUIT

generally gives greater distortion. This point should be investigated and the results compared with those already obtained.

(*c*) TRAPEZIUM METHOD OF INVESTIGATING DISTORTION

If a voltage from the modulating source is applied to the *X* plates of an oscillograph, while the modulated oscillation is applied to the *Y* plates, the trace on the screen has the

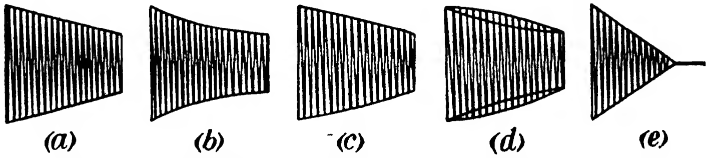

FIG. 112. TRAPEZIUM METHOD OF SHOWING DISTORTION IN MODULATION

outline of a trapezium as shown in Fig. 112 (*a*), which shows the shape to be expected if there is no distortion.

In order to obtain the trapezium, the time base of the oscillograph is switched off and leads are taken from the L.F. potential divider to the *X* and *E* terminals of the oscillograph. The modulated oscillation is applied to the *Y* plates by the mutual coupling shown in Fig. 110. The various shapes of

trapezium corresponding to various types of distortion are shown in Fig. 112.

Amplitude distortion gives curved upper and lower sides as at (*b*) or (*c*). Phase distortion produces double sides as in (*d*). If the modulation is increased to 100 per cent the trapezium becomes a triangle. On increasing the modulation depth still more, the triangle shortens and a line extends from its apex, as at (*e*), showing at once the existence of over-modulation. The trapezium method also allows the percentage modulation to be determined easily. Measuring the lengths of the two vertical edges L_1 and L_2, the percentage modulation is $\dfrac{L_1 - L_2}{L_1 + L_2} \times 100$.

Experiment 86. The Quartz Crystal Oscillator

The piezo-electric properties of quartz make it possible to use a crystal of this substance, when properly cut, as a standard of frequency and for fixing the frequency of a transmitter. The crystal stands between two parallel metal electrodes, with a very small air gap between the top electrode and the upper surface of the crystal plate. When a R.F. voltage is applied to the electrodes at a frequency equal to one of the frequencies of mechanical vibration of the crystal, the latter is thrown into resonant oscillation, the frequency of which is practically independent of temperature. An alternating p.d. is set up across the faces of the crystal when in vibration and this p.d., if applied between grid and cathode or between anode and grid of a valve oscillator, keeps the frequency of the oscillator constant and independent of variations which may take place in the valve or in the tuned circuit. The crystal has a very small damping coefficient, so that it is equivalent to a circuit of very high Q value.

A simple circuit, in which the quartz crystal is placed between anode and grid, is shown in Fig. 113, the valve being an Osram M.H.4 (indirectly-heated with 4 volts on the heater). Between grid and cathode is a resistance which should be 1–2 M Ω. The anode circuit contains a tuned L–C circuit whose frequency range includes that of the crystal. For a crystal giving 100 kc/s, suitable values are, for L, a 50-turns coil and for C a variable air condenser up to 0·0005 μF. Coupled to L is a coil of 300 to 400 turns to which an oscillograph is connected. The feed-back to the crystal is obtained

in this circuit through the grid-cathode capacitance of the valve. In order to set the crystal into vibration, the condenser C is slowly varied and the anode current is observed. When oscillation occurs, there will be a sudden drop in this current and the waveform of the oscillations may be seen on the oscillograph when its time-base frequency has been properly adjusted. It may be necessary to use one of the amplifiers of the oscillograph. A quartz crystal sometimes needs coaxing

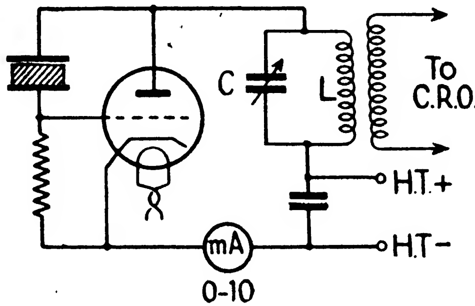

FIG. 113. QUARTZ CRYSTAL OSCILLATOR

into oscillation; this may be done by a gentle tap on the top of its case.

Having obtained oscillations, the way in which the output of the circuit varies with the setting of C should be investigated. Altering C in the neighbourhood of the resonance position, it will be found that as C is reduced, the output (measured by the double amplitude of the oscillograph trace) falls very sharply, but if C is increased, the fall from the maximum value is much less rapid. Setting C at a number of different values, the double amplitude (which is easier to measure than the actual amplitude) is observed on the oscillograph, keeping the amplifier control at a fixed position, this having been adjusted first to give a sufficiently large amplitude at resonance. A curve may then be plotted showing the relation between R.F. output and the condenser reading. In a transmitter the tuned circuit would be set so that the R.F. output is that corresponding to a point on this curve just below the maximum on the side of smaller slope, thus avoiding the instability associated with the sudden drop in output on the other side of the maximum.

A second way of connecting the crystal is to place it in parallel with the grid-cathode resistance. The oscillator then acts as a tuned anode-tuned grid oscillator in which the grid circuit controls the frequency. If the output curve, similar to the above, is plotted for this arrangement, it will be found to fall very steeply when C is increased beyond the value for maximum output, and to have its smaller slope on the side of lower condenser reading. In a transmitter using this type of circuit for frequency control, the tuning capacitance would thus be set, for stability, at a value a little below that giving maximum output.

CHAPTER XI

POWER SUPPLIES

THE experiments in this chapter are concerned with the provision, from the A.C. mains supply, of direct voltages (and power) suitable for the H.T. supply to a receiver or transmitter, or for other purposes.

Experiment 87. Half-wave and Full-wave Rectification using Metal Rectifiers

In half-wave rectification the rectifying element allows current to pass only on the positive half-cycles of the A.C.

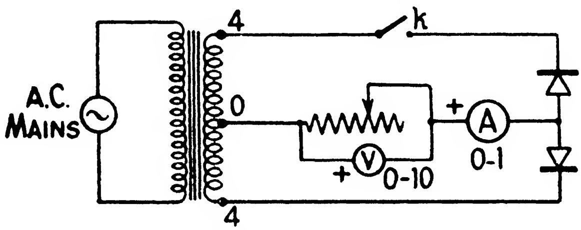

FIG. 114. CIRCUIT FOR HALF-WAVE AND FULL-WAVE RECTIFICATION USING METAL RECTIFIERS

supply. In full-wave rectification, two rectifying elements are arranged so that current passes during each half of the cycle. The change from half-wave to full-wave rectification is made by closing the switch *k* in Fig. 114, which shows the circuit to be used when two metal rectifiers connected back to back are available. These rectifiers may be single elements or they may consist of a unit with a centre terminal. In either case, the current must not exceed the rated value, which corresponds to a voltage of about 1 volt per element. If a resistance of 10 Ω is included in series with an element, a voltage of about 4 volts may be applied to the combination. The experiment will be described for single elements, but it may be made with larger units if proportional increases in all values (except current) are used.

The A.C. mains transformer has a centre-tapped secondary giving 4–0–4 volts, the centre tapping being connected

through a 2 amp. fuse, a rheostat of 10 Ω, and an ammeter (0–1 amp.) to the mid-point of the two rectifiers. Across the rheostat are connected a voltmeter (0–10 volts) and an oscillograph, the latter being used (on the amplifier terminals) to observe the current waveform. Using half-wave rectification first (i.e. *k* open), the current is adjusted to 0·3 amp.; and the oscillograph adjusted to show several pulses of current. These pulses are nearly, but not quite, the shape of half a sine wave. A drawing of the waveform should be made. The voltage across the rheostat is recorded and the power dissipated in the resistance is calculated in watts. The rheostat is then adjusted to give 0·4 and 0·5 amp. and the voltage measured and the power calculated at each of these values. It should be noted that the resistance concerned is different in each case.

Secondly, by closing *k*, full-wave rectification is used. The two rectifiers are then in operation alternately. Observations and measurements should be made as before and the results compared. A circuit of the type used here could be used for charging an accumulator, the cell being placed in series with the rheostat with due regard to polarity.

Experiment 88. Half-wave Rectification using a Diode

The purpose of this experiment is to set up a diode for use as a half-wave rectifier and to examine the voltage output and current under various types of load. An Osram U.14 valve, which is a double diode requiring a filament current of 2·5 amperes at 4 volts, is used for the experiment, one anode only being employed for half-wave rectification. A mains transformer with a 150-volt or 200-volt secondary winding provides the anode voltage, while the filament current is provided either from large accumulators or from a 4-volt secondary winding on the transformer.

The load consists of a condenser C (4 μF) and a resistance R which may be used separately or in parallel, as shown in Fig. 115. Across the load is an electrostatic voltmeter (0–300 volts) and an oscillograph for investigating the output voltage waveform. The resistance R must be capable of dissipating up to about six watts and may be constructed of two or three units of 10,000 Ω each in parallel, the units consisting of two 5000 Ω 2 W resistors in series. In the anode circuit, the current is measured by a milliammeter (0–100 mA) and passes

through a resistance R_1 of 100 Ω across which the second pair of oscillograph plates is connected to show the current waveform, using one of the oscillograph amplifiers if necessary.

Having set up the circuit, an experiment should be made first with the capacitance load only. On switching on, a pulse of current, which will be noticed on the milliammeter, will flow to charge C to the peak voltage. No further current will flow. The voltage across C, measured by the voltmeter, will be found to be equal to the peak secondary voltage.

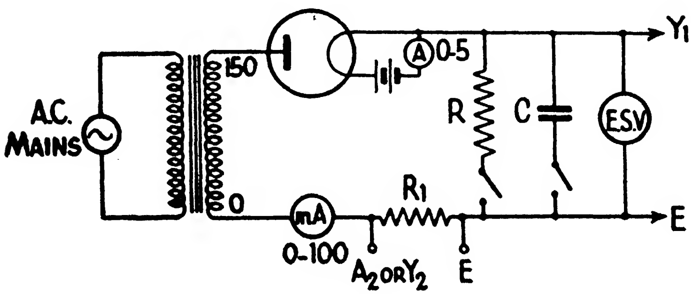

FIG. 115. HALF-WAVE RECTIFICATION BY A DIODE

Secondly, a resistance load only should be used, R being set at 5000 and 10,000 Ω in turn. At each value, the current and voltage are measured and the current and voltage waveforms are observed. The voltage waveform will be seen to be of the same shape as the current waveform. Thirdly, a load consisting of a capacitance and a resistance in parallel should be used, the value of R being 5000, 10,000, and 50,000 Ω in turn. Commencing with $R = 5000$ Ω, the current and output voltage are measured and their waveforms examined. The voltage waveform will be found to be much more smooth, but will show a pronounced ripple. By bringing the two oscillograph traces together it will be seen that during each current pulse the condenser charges up and then leaks through R in the interval between pulses until charged again by the next pulse. The output voltage should be compared with the peak value previously measured. Proceeding to similar observations with the larger values of R mentioned, it will be seen that the ripple becomes less pronounced and the output voltage is somewhat greater as R is increased. Diagrams of the

current and voltage waveforms should be drawn. The ripple will be seen to have the same frequency as the supply.

Experiment 89. Full-wave Rectification using a Diode

Full-wave rectification is more commonly used in power packs to supply the H.T. for a receiver, because it enables both half-cycles of the A.C. supply to be used. In addition to the double diode (U.14), a mains transformer is required with a centre-tapped secondary giving 200–0–200 volts, and

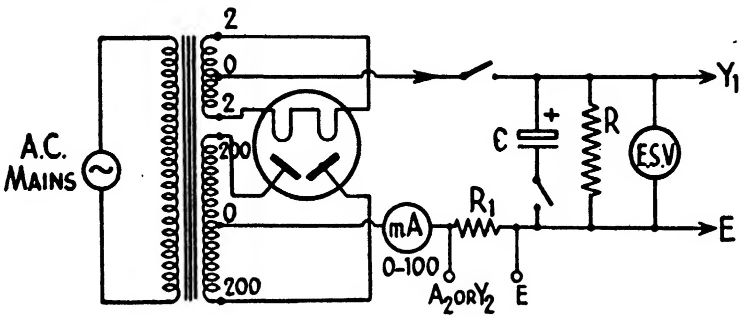

FIG. 116. FULL-WAVE RECTIFICATION USING A DOUBLE DIODE

also, preferably, a centre tapped secondary giving 2–0–2 volts for the filament. If the latter is not available, a simple 4-volt secondary may be used, or even accumulators, but in this case the adjacent peaks of rectified current will not be quite equal. The circuit is shown in Fig. 116, with a resistance load R and, if desired, condenser smoothing by means of an electrolytic condenser C of 8 μF. An electrolytic condenser may be used since the output is not alternating, but only fluctuating; care must be taken, however, to see that its connexions are made with the proper polarity.

As in the experiment on half-wave rectification, an electrostatic voltmeter (0–300 volts) is used to record the output voltage across R and an oscillograph is connected with one set of plates across R and the other set across R_1, the latter giving the current waveform. R may consist of a number of 10,000 Ω resistors from which loads of 20,000 Ω, 10,000 Ω, and then, by parallel connection, 5000 Ω and 3330 Ω may be obtained.

First, using $R = 10{,}000\,\Omega$, the current and voltage waveforms are observed, superposing the two traces for comparison. This is done without C and then with C connected and diagrams of the waveforms are drawn for each case. It will be noticed that the frequency of the ripple is twice that of the supply. Secondly, the relation between voltage and current for various values of the load is investigated both with and without the smoothing condenser. R is set at the values mentioned above, care being taken to switch off before changing R, and the output voltage is measured for each. From the

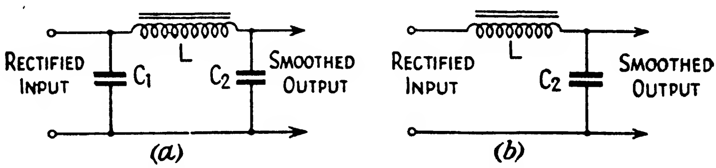

FIG. 117. (*a*) INPUT CONDENSER FILTER; (*b*) CHOKE INPUT FILTER

readings a curve is plotted to show the relation between output voltage and current. The maximum current rating of the valve is 120 mA, which must not be exceeded in these measurements. A similar set of readings is then obtained with the smoothing condenser included.

If an electrostatic voltmeter is not available, a Taylormeter on the 250-volt D.C. range may be used. Its resistance will be at least $250{,}000\,\Omega$, so that the current taken by it will not exceed 1 mA, which may be neglected.

Experiment 90. Smoothing Circuits

In the two previous experiments the smoothing effect of a condenser alone has been investigated. If the output of a half-wave or a full-wave rectifying unit is to be suitable for a H.T. supply, it must be well smoothed. The two principal types of smoothing circuit (or filter) are shown in Fig. 117. In the input condenser filter at (*a*), the rectified input is connected to the condenser C_1, which acts as a reservoir condenser, discharging into the load through a L.F. choke L. In the choke input filter at (*b*), the input feeds the load through the L.F. choke L. In both filters, the condenser C_2 acts as a by-pass to any ripple which may pass the choke.

The circuit is similar to that used in the previous experiment, with the addition of the smoothing components, which are arranged with switches as shown in Fig. 118, so that the various components may be introduced as desired to show their action in the filters mentioned. As before, an oscillograph is connected across the load and also across R_1 so that both output voltage and current waveforms may be observed. To change from full-wave to half-wave rectification, a key, placed in one anode lead, is opened. R should be about

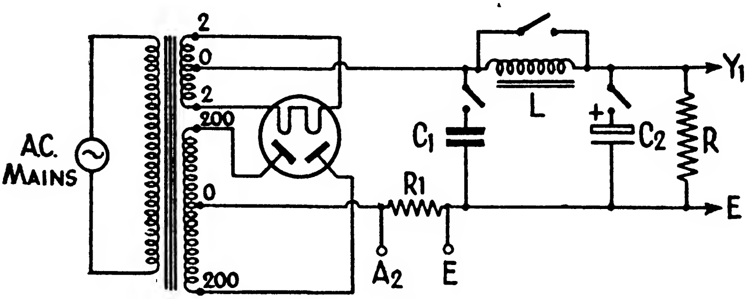

FIG. 118. EXPERIMENTAL POWER PACK

10,000 Ω, C_1 a 2 μF or 4 μF condenser, C_2 a 8 μF electrolytic condenser and L an iron-cored choke of inductance 40 to 60 H.

In the observations, which should be made in the order which follows, the two oscillograph traces (of current and output voltage waveforms) should be brought near together, if not actually superimposed, so that the relation between them may be seen. Also, careful diagrams of the traces should be made for each case.

(*a*) With choke short-circuited and condenser switches open, the waveforms of current and of voltage across R are observed, for both the half-wave and full-wave cases.

(*b*) The reservoir condenser C_1 is introduced and its effect on the waveforms observed in both cases.

(*c*) The choke L is then added to the circuit and the observations repeated.

(*d*) Finally the condenser C_2 is introduced and the observations made with the input condenser filter which has thus been built up.

The D.C. output voltage may also be measured by an electrostatic voltmeter across R, the increase in its value as the smoothing is increased being noted.

(*e*) Proceeding in the same manner, the choke input filter, shown in Fig. 117 (*b*), is built up, first noting the effect of the choke alone, and secondly, the effect of adding C_2.

This should be done for both half-wave and full-wave rectification as before, noting particularly the difference between the shapes of the ripple when the smoothing is only partial, i.e. with C_1 alone and with L alone.

Experiment 91: The Mercury-vapour Rectifier

The mercury-vapour diode was the subject of Experiment 55, in which its characteristic was investigated. Its advantage over the ordinary diode is that it is able to pass much greater currents with only a small voltage drop across it and is therefore used where greater power is to be handled.

In addition to the usual precautions necessary when using such a valve, viz. the anode voltage V_a must not exceed 20 volts, and the filament heating must be switched on half a minute before the H.T., it is desirable, when rectifying A.C., to prevent the rise and fall of V_a which would occur as the applied voltage rises from 0 to the A.C. peak and falls again. This is accomplished by inserting a L.F. choke of about 1 H which must be capable of carrying the maximum rated current of the valve. In the case of the GU50 valve, used in this experiment, the rated maximum is 250 mA. Its filament is supplied by a 4-volt cell.

The purpose of the experiment is to show the relation between the D.C. output voltage across an anode load, and the A.C. input voltage for various constant currents through the valve. Fig. 119 shows the circuit which is used. The input voltage V_1 is obtained from a "Variac" transformer on the A.C. mains and is measured by an A.C. voltmeter (0–250 volts). The anode load, in addition to the choke, consists of two 1000 Ω rheostats R, in series, with a Taylormeter (0–250 volts D.C. range) connected across them to measure the rectified voltage V_2. An 8 μF electrolytic condenser, connected with proper polarity, provides considerable smoothing. The anode current is recorded by a milliammeter (0–150 mA).

The filament heating is switched on and, after half a minute, with R at its maximum value, the A.C. voltage is applied and increased to 150 volts. R is then adjusted to give a mean anode current of 60 mA and V_2, the voltage across R, is read. The A.C. voltage is then adjusted to a lower value, say 120 volts, and R is readjusted to keep the current at 60 mA, when V_2 is again read. Proceeding in this way by steps of 20 to 30 A.C. volts, and at each stage adjusting R to keep the

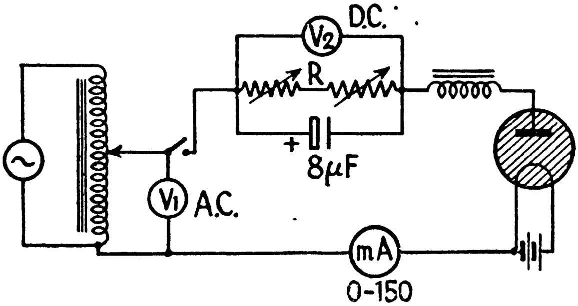

FIG. 119. MERCURY-VAPOUR RECTIFIER

current constant, a series of corresponding readings of V_1 and V_2 is obtained.

A second set of readings for a current of 90 mA should then be obtained in the same way.

For each of these cases, a graph is plotted showing the relation between V_1 and V_2. The points will be found to lie on practically a straight line for each current.

A test should be made of the smoothing effect of the condenser, by disconnecting it and measuring V_2 at one of the values of V_1 and current used in the measurements above. It will be found to be much less than when the condenser was included, and it is also much less steady.

CHAPTER XII

ADDITIONAL EXPERIMENTS AND NOTES

Experiment 92. A Three-valve Straight Receiver

THE principles of R.F. amplification, detection, and L.F. amplification which have been dealt with in previous experiments are applied here to construct a complete battery-operated simple receiver. The circuit diagram (Fig. 120) shows the values of all the components, many of which may

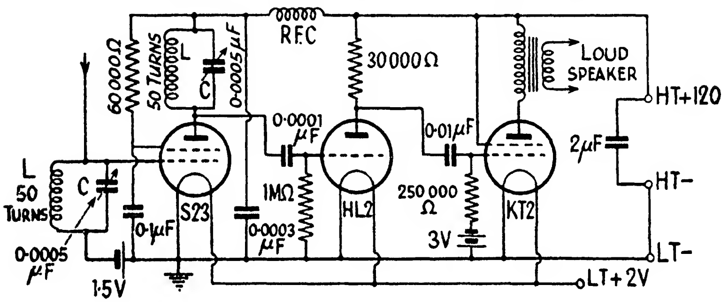

FIG. 120. THREE-VALVE STRAIGHT RECEIVER

be fixed to a board which also carries the valve sockets. It will be seen that the receiver comprises one stage of R.F. amplification using a S.G. tetrode and a grid detector coupled by resistance-capacity coupling to a beam tetrode operating as an output pentode and supplying a loud-speaker through a matching transformer. The valves are, in turn, S.23, H.L.2, and K.T.2 (Osram), all of which take 2 volts on the filament.

The R.F. amplifying stage is of the normal tuned-anode type, with the screen voltage obtained by dropping the H.T. voltage of 120 volts through a 60,000 Ω resistance. The output valve is a kinkless tetrode, which has pentode characteristics. Its anode load for maximum output is 12,000 Ω, which will be secured if the output transformer has a step-down ratio of 40 : 1, and the loud-speaker has a resistance of about 8 Ω.

In fitting up the receiver, consideration should be given to the lay-out of the components if confusion is to be avoided

and good results obtained. The two tuned circuits should be arranged so that the coils are reasonably distant from each other with their axes at right angles. The small fixed condensers should be placed near to anode and grid terminals to which they are to be connected so that the connexions are short.

When the circuit has been completed, the receiver should be tuned to a broadcast transmission, setting the tuned-anode condenser at its mid-point, tuning the aerial circuit and then tuning the anode circuit for maximum reception. The aerial tuning dial may be calibrated by tuning in this way to various broadcasting stations whose frequency is known, or by using a modulated R.F. oscillator coupled to the aerial tuning coil.

Experiment 93. Direction- and Sense-finding by Loop Aerial

For this experiment, which has for its purpose the investigation of the direction-finding and sense-finding properties of a loop aerial, the loop should consist of some 15 to 20 turns of fairly stout copper wire (say No. 16) fixed to a frame to form a circle or a hexagon of about 2 feet in diameter, set vertically and arranged to rotate about a vertical axis. It carries either a pointer moving over a fixed degree scale (0°–360°) or a degree scale moving past a fixed pointer.

The loop is connected to a fixed coil of about 100 turns inductively coupled to the aerial tuning coil of the three-valve receiver of Experiment 92, or any receiver employing R.F. amplification, by being wound on this coil, the centre point of the loop coil being earthed. In this way, the E.M.F. induced in the loop by the electromagnetic wave may be received separately or may be combined with that from a straight aerial. Coupled to the anode tuning coil of the R.F. amplifying valve is a small coil of about 5 turns to which a cathode-ray oscillograph or valve voltmeter is connected. This enables the amplified signal voltage to be observed. The number of turns in this coil must be chosen so that the damping of the tuned circuit is not seriously affected. The modifications in the R.F. side of the receiver are shown in Fig. 121.

(a) Measurements with Loop Aerial Only

The receiver is set up with the loop aerial, but without earth connexion, and is tuned to receive a broadcast transmission. On rotating the loop, the change of intensity showing

two maxima and two minima in a complete rotation is observed. A cathode-ray oscillograph is connected to the small coil coupled with the anode tuning circuit and, using the amplifiers on the 2 $H.F.Y_1$ position, the carrier waveform is observed. Setting the loop at definite positions equally spaced at about 10° apart in a complete rotation, the double amplitude of the trace on the oscillograph screen is measured

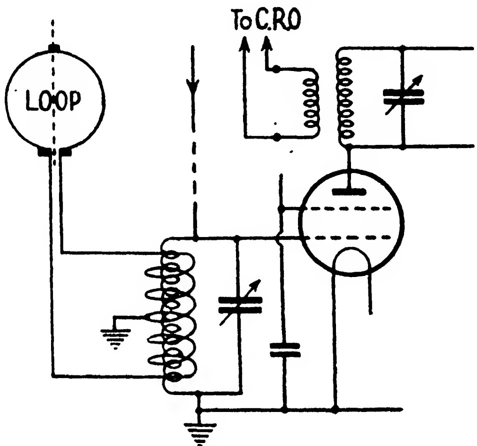

FIG. 121. ARRANGEMENTS FOR LOOP AERIAL

at each point. Modulation may cause some disturbance, but a reasonable measurement can usually be made. On plotting a graph showing the relation between amplitude and scale reading in degrees, it will be noticed that the minima are sharper than the maxima, which are relatively flat. Using phones or a loud-speaker and setting the loop carefully for a minimum, the position of the line along which the transmitter is situated is determined; it will be along the *axis* of the loop. If a compass needle is used in conjunction with the loop, this direction can be specified, but the sense of the transmitter cannot be found.

(*b*) SENSE-FINDING

To obtain the sense of a transmitter, the loop is combined with a vertical aerial. Such an aerial, about 6 to 8 feet long, is connected to the aerial tuning circuit in the usual way, and

the earth connexion completed. On rotating the loop, it will be found that maximum reception occurs at one position and minimum reception in the opposite orientation (i.e. when turned through 180°). Thus the combination of loop aerial and vertical aerial is unsymmetrical and may be used for finding the sense of the transmitter. In order to find which edge of the loop points towards the transmitter when the reception is a maximum, an oscillator giving a signal modulated at 400 c/s is connected to a vertical aerial at some distance in the laboratory and the set adjusted to receive the signal. On rotating the loop, the position required is easily found and may be marked with an arrow on the top of the loop.

In order to find both sense and bearing of a transmitter, the sense is found as in (*b*) and then, disconnecting the vertical aerial, the bearing is determined accurately by setting on the minimum as in (*a*).

Experiment 94. The Dynatron Oscillator

When a valve is used on a part of its I_a–V_a characteristic which has a negative slope, i.e. where it has a negative resistance, it is termed a dynatron. In this region an increase in voltage, say ΔV_a, is accompanied by a decrease in current, say, ΔI_a, and if the voltage is varying, the current is in antiphase with it. The negative resistance implies that the system is a source of power (a positive resistance being one which absorbs power) and if the power from this source is delivered to a L–C circuit, the phase relation mentioned above being that required for the maintenance of oscillations, then oscillations will occur at the natural frequency of the circuit and they will build up until energy is dissipated at the same rate as that at which it is being supplied.

A S.G. tetrode (such as Osram S.23) provides a negative resistance when, for suitable values of control grid voltage V_g and screen voltage V_s, the I_a–V_a characteristic has a negative slope between certain values of V_a. In order to operate a dynatron oscillator, V_s is maintained at a higher value than V_a, while V_g is generally the normal grid bias between − 3 and − 6 volts.

The circuit is shown in Fig. 122 and it may be used, according to the constants of the tuned circuit, for producing audio-frequency or radio-frequency oscillations.

For L.F. oscillations, L should be an air-cored inductance of about 0·2 H and C a variable 0–1 μF condenser. Headphones may be coupled to L by a coil of 200 turns. Suitable initial values of the voltages are: $V_g = -4{\cdot}5$, $V_a = 48$, and $V_s = 150$ volts. Before switching on, care should be taken to see that the milliammeter is set on a high range because the anode current may become negative, although this should be avoided by adjustment of V_a or V_s. The waveform of the

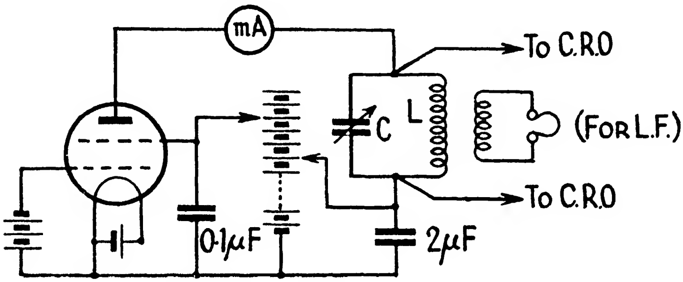

FIG. 122. DYNATRON OSCILLATOR

oscillations is observed by a cathode-ray oscillograph connected across the oscillatory circuit.

Having obtained oscillations, their waveform is observed and it will be noted that it is a good sine curve, showing no perceptible harmonics. Then, keeping V_g and V_a fixed, the effect of increasing V_s up to 200 volts is observed. The greater supply of energy results in an increased amplitude, but with no change in frequency.

Then, returning V_s to a lower value, say 150 volts, the effects of changing V_a to values within the range 30 to 60 volts should be observed. In doing this, the anode current should be carefully watched, as well as any changes in waveform.

If it is desired to set the oscillator at a standard frequency, the conditions for best oscillation are restored and the frequency set (by adjustment of C) by reference to a standard tuning fork as for the audio-frequency oscillator of Experiment 65.

Also, the oscillations of the coil on its own self-capacity may be observed if C is disconnected.

For R.F. oscillations, a coil of 50 or 100 turns and a variable air condenser up to 500 $\mu\mu$F may be used. The waveform will

be observed on the oscillograph. It will be found that the value of V_g is more critical than in the former case. Observations on the effects of changing the grid, screen, and anode voltages may be made as before.

Modulation may be effected in the R.F. oscillations of a dynatron by applying the modulating voltage in series with either the screen voltage or the grid voltage. The method follows that for grid modulation as in Experiment 85. It will be found that in screen modulation the tendency to distortion is less.

ADDITIONAL NOTES

Nickel-iron Alkaline Accumulators

THESE accumulators have positive plates of nickel oxide and negative plates of iron in a solution of caustic potash of specific gravity 1·170. The plates are constructed in a special way with the substances mentioned above enclosed in perforated nickel-plated compartments, the outer casing of the cell being of metal, also nickel plated. As compared with the lead-acid cell, these cells have the advantages of a very robust mechanical construction and, what is more important, the ability to withstand excessive rates of discharge without damage. They may also be left in a discharged condition for long periods without deterioration and have a reasonably low internal resistance, this being about five times that of the ordinary lead-acid cell. On the other hand, the E.M.F. of a single cell is only about 1·4 volts and the capacity of these cells is found to be considerably reduced if the temperature is low.

The following information will be found useful if alkaline cells of this type have to be charged and used. Such cells are generally rated at the 8-hour rate and should not be discharged below 1·10 volts on load. The specific gravity of the alkaline solution does not change with the state of discharge as does the acid in a lead cell. Charging is continued until the individual cells show 1·75 volts on charge. Gassing occurs throughout the whole charging period, so that the voltmeter test is the only one which can be employed. After removal from the charging bench, a cell generally shows about 1·6 volts.

In a smaller form, these cells are also used for H.T. supply, a number of them being packed into a box container to form a Milnes H.T. unit giving 120 volts with tappings. The advantage of this type of cell over the small dry cell of the ordinary H.T. battery will be obvious from what has been said above. For charging such a unit, the cells are connected in parallel in groups of four, by means of a special switch on the case, and the charging may then be done at a slow rate by connecting to a 6-volt lead accumulator.

Litz Wire

When an alternating current of high-frequency is passed through a wire, an effect called the skin effect is found to occur. The current tends to confine itself to the outer portions of the cross-section of the wire, which therefore offers a much higher resistance to the current. In transmitter tuning coils, this tendency is reduced by using copper tubes instead of solid wires for the coils. Litz wire is a flexible wire devised for the purpose of reducing the skin effect. It consists of a large number of fine enamelled wires plaited in such a way that the outer surface of the conductor is composed of equal amounts of each wire. In this way, the distribution of high-frequency current over the cross-section is much more uniform.

If a coil is wound of Litz wire, it will have a high-frequency resistance not much greater than its D.C. value and hence the Q of such a coil will be very large. The measurement of Q could be carried out as in Experiment 69.

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